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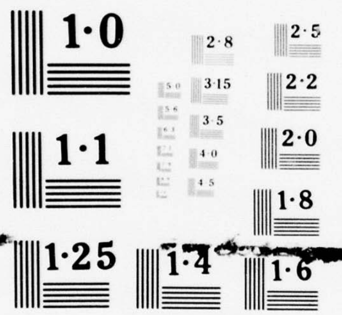
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TURBINE ENGINE VARIABLE CYCLE SELECTION PROGRAM

MCDONNELL DOUGLAS CORPORATION
MCDONNELL AIRCRAFT COMPANY
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APRIL 1977

TECHNICAL REPORT AFAPL-TR-77-17

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1 JULY 1973 - 31 JANUARY 1977

AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This technical report has been reviewed and is approved for publication.

For the Commander

Joseph M. Frederick
Project Engineer,
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A systematic engine/airframe evaluation procedure was developed and used to assess interactions for fixed and variable geometry engine concepts in tactical aircraft. The evaluation procedure provides a rapid and inexpensive technique for evaluations of advanced engine concepts for extensive matrices of potential aircraft maneuverability and multi-mission requirements.

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The evaluations were conducted using parametric, fixed cycle turbojet and mixed flow turbofan data provided by the General Electric Company, and variable geometry turbine turbojet data provided by Detroit Diesel Allison and AFAPL. AFAPL obtained the engine data from a Pratt and Whitney Aircraft Company parametric engine computer program.

The results of the program verify the parametric aircraft representations obtained from the evaluation procedure. For specified system requirements, optimized aircraft designs are obtained which exhibit size, weight and performance characteristics of those which would have been estimated using the more time consuming and expensive design/performance analysis techniques. Further, the evaluation procedure permits design selections and trade-offs accounting for engine/airframe/requirement interactions which have previously been undefined in the advanced design process.

The use of engines from three manufacturers resulted in differing technologies and design duty cycles and, thus, precluded direct comparisons. However, the results of these evaluations indicate significantly reduced installation losses with the variable geometry engines. Further, the combined effects of variable turbines and airflow scheduling reduce aircraft TOGW sensitivity to cycle design variables.

FOREWORD

This report was prepared by the McDonnell Aircraft Company (MCAIR), a division of the McDonnell Douglas Corporation, St. Louis, Missouri for the Air Force Aero Propulsion Laboratory, Air Force Systems Command, United States Air Force, Wright-Patterson Air Force Base, Ohio. This study was performed under Air Force Contract F33615-73-C-2070, "Turbine Engine Variable Cycle Selection Program." The work was performed from July, 1973 through January, 1977, with Mr. Joseph M. Frederick (AFAPL/TBA) of the Air Force Aero Propulsion Laboratory as Project Engineer. The MCAIR efforts in this program were accomplished under the direction of R. E. Martens, F. C. Glaser, and W. B. Weber with the assistance of J. T. Mack, M. F. McDevitt, G. A. Phariss, B. T. Phelps and D. L. Schoch.

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SYMBOLS AND ACRONYMS

Symbol	Definition
A	area - ft^2
ACCEL	acceleration - ft/sec^2
AEX	nozzle exit area - ft^2
AR	wing aspect ratio
BPR	engine bypass ratio
C_{L_d}	wing conical camber
D	drag - lb, or diameter - in
EM	energy maneuverability Mach/altitude point
F_N	engine net thrust - lb
F_{NP}	net propulsive force - lb
FPR	fan pressure ratio
L	lift - lb, or length - ft
LER/$\bar{c}$	wing leading edge radius to chord ratio
N_z, n_z	normal load factor - g
OPR	engine cycle design overall pressure ratio
P	static pressure - lb/ft^2
P_s	specific excess power - ft/sec
R	range - NM
RAD	radius - NM
R_f	range factor - NM
SFC	specific fuel consumption, lb/hr/lb
TIT	engine turbine inlet temperature, °F
T.O.	take-off
TOGW	aircraft take-off gross weight - lb
t/c	wing thickness to chord ratio
T/W	thrust to weight ratio
V	flight velocity - ft/sec
W	weight - lb
W_A	inlet airflow rate - lb/sec
W/S	aircraft wing loading - lb/ft^2
λ	wing taper ratio
Λ(LAM)	wing sweep angle - degrees
Subscripts	
9	nozzle exit
10	maximum fuselage cross-section
∞	freestream

SYMBOLS AND ACRONYMS (Continued)

Acronyms	Definition
AFAPL	Air Force Aero Propulsion Laboratory
CADE	Computer Aided Design Evaluation computer program
ESIP	Exhaust System Interaction Program
IOC	Initial Operational Capability
LCC	Life Cycle Cost
O&M	Operations and Maintenance
PSIP	Propulsion System Installed Performance computer program
RDT&E	Research Development Test and Evaluation
ROC	Required Operational Capability
SEARCH	Optimization computer program
SURFIT	Surface Fit computer program
VCE	Variable Cycle Engine
VGT	Variable Geometry Turbine

SUMMARY

Engine cycle selection is a complex task which must be based on a thorough understanding of the propulsion system influences on aircraft size, cost, and performance. The evolution of variable cycle engines will increase both the complexity of the selection process and the importance of propulsion system/airframe interactions. The MCAIR "Turbine Engine Variable Cycle Selection Program" being conducted under AFAPL Contract F33615-73-C-2070 is specifically directed toward development of systematic design selection procedures and the use of those procedures to evaluate advanced engine concepts in tactical fighter aircraft. This report presents a summary of the results obtained from this two-phase program. Reference 1 presents a more detailed discussion of the Phase I results and Phase II is reported in References 2 and 3.

In Phase I, a Fighter Engine/Airframe Evaluation Procedure was developed. The Evaluation Procedure permits the calculation of the size, mission, and performance characteristics of a systematically selected matrix of aircraft designs. The results of these computations are used to define mathematical equations which relate aircraft take-off gross weight, mission radii, and performance capabilities with engine and airframe design variables. Finally, an optimization procedure is used, in conjunction with these equations, to determine the minimum take-off weight aircraft design capable of achieving specified mission and performance requirements.

The Evaluation Procedure permits consideration of eleven design variables and up to seventeen mission radius and performance requirements. The results permit clear identification and evaluation of the impact of propulsion system/airframe interactions on system characteristics. Further, the effects of aircraft mission and performance requirements on aircraft size and operational flexibility can be readily determined.

Fixed cycle engines were evaluated in Phase I. The General Electric Company (GE) provided parametric families of twin-spool, fixed cycle turbojet and mixed flow turbofan engines for these evaluations. The Evaluation Procedure was used to develop parametric aircraft characteristics correlation equations for both types of engines. In the Phase I aircraft sizing and performance analysis, an interdiction mission with a supersonic dash requirement at 2700 lb/ft^2 dynamic pressure was used for fuel sizing. As a result, all the aircraft represented in the correlation equations were constrained to be compatible with this specialized, demanding operational requirement. This constraint limited the flexibility desired for evaluations of interactions between operational and performance requirements and engine/airframe design characteristics. The variables used for thrust and fuel sizing in Phase II produced aircraft characteristics

relationships which significantly increased the capability to conduct such evaluations.

Design layouts and performance analyses were used in Phase I to verify the technical validity of aircraft designs selected using the Fighter Engine/Airframe Evaluation Procedure. These verifications indicated realistic representations of aircraft size and weight characteristics and sufficient accuracy in the parametric aircraft characteristics for meaningful trade-off and concept screening tasks in the advanced aircraft design process.

Variable geometry turbine (VGT) turbojets were evaluated in Phase II. Parametric families of VGT turbojet designs were provided by Detroit Diesel Allison (DDA) and the AFAPL. The DDA engines were all single spool designs which used a very advanced compressor concept. The engines provided by AFAPL were obtained using a Pratt & Whitney Aircraft Co. (P&WA) parametric turbojet engine computer program, Reference 4. These engines encompassed both single and twin spool design concepts.

The Phase II aircraft characteristics correlation equations produced significant improvements in flexibility for requirements interaction evaluations compared to the Phase I data. The fuel and thrust sizing elements of a parametric strike mission were used as variables in the aircraft sizing and performance analysis. Consequently, the Phase II results identify engine, airframe and aircraft characteristics interactions for extensive ranges of mission cruise, dash, and performance requirements. In addition, the Phase II data permitted evaluations of the aircraft systems for the Phase I requirements. The Phase II results also provide additional capability to identify important engine operating characteristics affecting design selection.

The Engine/Airframe Evaluation Procedure developed during this program represents a valuable tool for the advanced aircraft design process. It has been used to establish a meaningful data base for selected engine/airframe concepts. Further, rapid and inexpensive convergence of the potential design matrix has been demonstrated, thereby permitting concentration of engineering development efforts in high yield areas. Using the procedure, it has been determined that variable geometry turbine turbojet engines, with appropriate airflow scheduling, produce attractive performance for both subsonic and supersonic operation. Further, such engines reduce aircraft sensitivity to engine design variable changes and, thus, these results indicate greater flexibility for multiple mission applications with the VGT concepts.

1. INTRODUCTION

The use of variable cycle engine concepts will increase the significance of propulsion system/airframe interactions and the complexity of the engine cycle selection. In future aircraft development programs, engine and airframe design selections must be based on clearly defined relationships between aircraft characteristics and engine design and operating parameters. Consequently, a systematic procedure is required which will properly account for propulsion system/airframe interactions in the determination of those relationships.

The initial development of an engine cycle selection procedure, based on integrated propulsion system/airframe characteristics, was accomplished during the AFAPL sponsored Exhaust System Interaction Program (ESIP), Reference 5. The ESIP procedure uses an optimization technique to identify the engine cycle and airframe design which would produce the minimum achievable aircraft takeoff gross weight (TOGW) and accomplish a specified mission radius and combat performance requirement.

Although very successful in achieving its objectives, the ESIP was limited in scope. For example, only the minimum TOGW aircraft was obtained and its performance characteristics defined. Therefore, no data were obtained which would permit systematic evaluations of propulsion system/airframe interactions or allow the engine companies to determine component technology development needs in terms of aircraft system payoff potential. Trade-offs of mission/performance requirements versus aircraft TOGW, or cost, would have required repeated optimizations and would, therefore, have been prohibitively time consuming and expensive.

The major emphasis of the first phase of the "Turbine Engine Variable Cycle Selection Program" is the development and demonstration of an engine evaluation and selection procedure for advanced fighter aircraft. Provisions for evaluating propulsion system/airframe interactions, aircraft mission/performance requirements trade-offs, and engine technology development requirements by the engine companies are prerequisites of the procedure.

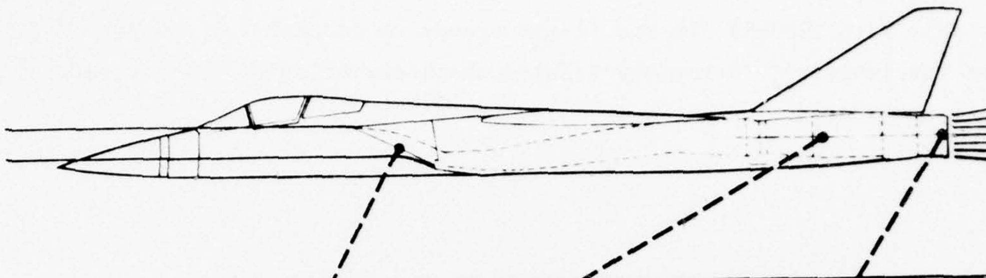
The following sections present MCAIR's approach for engine/airframe evaluations and a description of the Fighter Engine/Airframe Evaluation Procedure. The results obtained from evaluations of fixed cycle turbojets and turbofans are summarized in Section 4. Section 5 presents evaluation results for variable geometry turbine turbojets. Conclusions are presented in Section 6.

2. PROGRAM APPROACH

Potential payoffs for advanced engine concepts must be assessed in terms of overall system characteristics such as take-off gross weight (TOGW), life cycle cost, and operational flexibility. These characteristics are directly related to the aircraft system mission and performance requirements. Consequently, in a systematic procedure for the evaluation and selection of engines, system payoff potential must be evaluated as a function of mission and performance requirements. Phase I consisted of the development of an Engine/Airframe Evaluation Procedure and the utilization of that procedure to evaluate advanced technology fixed cycle engine aircraft systems, Reference 1. Phase II encompassed utilization of the Procedure to evaluate aircraft using variable geometry turbine turbojets, References 2 and 3.

A prerequisite for a viable procedure is that it properly accounts for propulsion system/airframe interactions in the determination of aircraft size and performance. As shown in Figure 1, such interactions can be identified in terms of throttle-dependent and size-dependent force increments. The throttle-dependent interactions are represented by increments in inlet and nozzle/aft-end drag. These drag increments, which are caused by variations in flow characteristics or geometry, are the result of changes in engine power setting. The lift and drag of the aircraft can also be affected by the relative size of the propulsion system and airframe. Force increments resulting from changes in relative propulsion system size are defined such that they are independent of engine throttle setting.

Aircraft mission and performance requirements also interact with the propulsion system size and thrust and the aircraft design as shown in Figure 2. The development of efficient engine/airframe designs must identify and properly account for such interactions. For example, in fighter aircraft, the engine size is usually established by one or more specific excess power (P_s) requirements at given Mach numbers, altitudes and power settings. The net propulsive force (F_{NP}), and therefore the engine thrust required to achieve the specified performance (P_s), is a function of aircraft weight (W), lift to drag ratio (L/D), and flight velocity (V), Figure 2. Design variables affect F_{NP} and L/D and these interact to define the engine size required to achieve a specified performance requirement. Similarly, aircraft fuel volume requirements are related to



	INLET GEOMETRY AND AIRFLOW	ENGINE GEOMETRY	NOZZLE GEOMETRY AND EXHAUST FLOW
• THROTTLE DEPENDENT	$\Delta CD_I = f(W_A)$	N/A	$\Delta CD_N = f\left(\frac{AEX}{AEX_{MAX}}, \frac{PEX}{P_\infty}\right)$
• SIZE DEPENDENT	$\Delta CD_I = f(A_{CAPT})$	$\Delta CD = f(L_{ENG}, D_{ENG})$	$\Delta CD_N = f\left(\frac{AEX_{MAX}}{A_{MAX_{FUSELAGE}}}\right)$

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FIGURE 1
PROPULSION SYSTEM - AIRFRAME INTERACTIONS

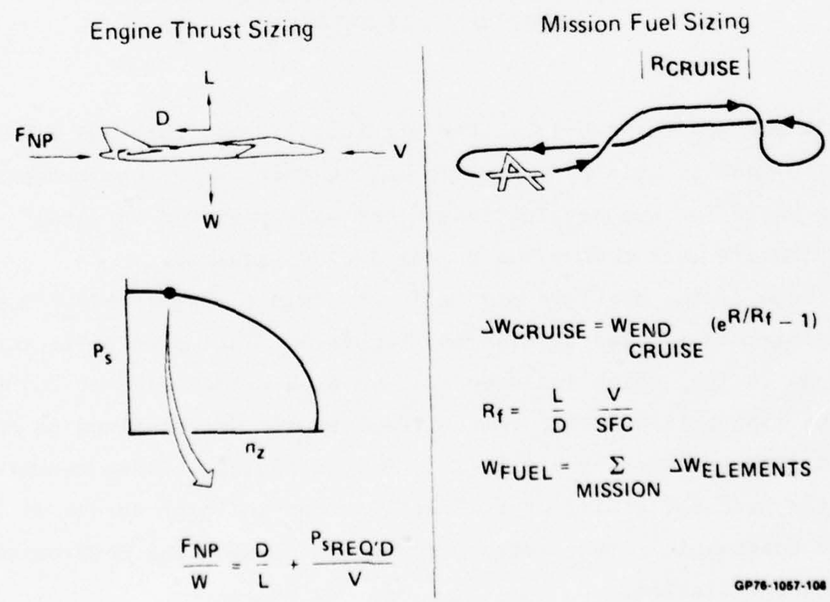

FIGURE 2
AIRCRAFT - REQUIREMENTS INTERACTIONS

L/D and engine fuel consumption (SFC) by means of an exponential range factor (R_f). Thus, design variables also affect the physical size of the airframe required to achieve a specified mission radius.

The MCAIR airframe and engine designs considered in this program are compatible with 1980-85 IOC and flight speeds up to Mach 2.5. Figure 3 illustrates the important technology-related characteristics of the aircraft and engines considered.

AIRFRAME

- RELAXED STATIC STABILITY
- FLY-BY-WIRE CONTROL SYSTEM
- DECAMBER FLAP
- VARIABLE CAPTURE AREA INLETS
- CONFORMAL WEAPONS CARRIAGE
- INTERNAL 25 MM GUN
- ADVANCED AVIONICS
- 33% COMPOSITE

ENGINE

PHASE I

- FIXED CYCLE
  - TURBOFAN
  - TURBOJET
- T/W ~ 6-10
- $T.I.T._{MAX} = 2800^{o}F$
- DUAL ROTOR
- C-D NOZZLE

PHASE II

- VGT TURBOJETS
- T/W ~ 8-12
- $T.I.T._{MAX} = 3200^{o}F$
- SINGLE & DUAL ROTOR
- C-D NOZZLE

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FIGURE 3
PHASE I AIRCRAFT AND ENGINE TECHNOLOGY
1985-90 M = 2.5 CAPABILITY

MCAIR and AFAPL established the fighter aircraft role and mission requirements to be used in this program. To insure that these requirements provided a realistic basis for such evaluations, they were reviewed in detail with the USAF fighter aircraft user commands and modified as required.

In Phase I, the aircraft size and performance characteristics were defined using an Interdiction Design Mission, Figure 4. This mission is characterized by a 400 nm radius, which includes a 50 nm dash at Mach 1.9 at 20,000 ft. altitude. The most critical performance requirements were defined at Mach 1.6, 35,000 ft. altitude, and Mach 0.9, 20,000 ft. altitude. These requirements, which combine the need for efficient fuel utilization and high thrust at both subsonic and supersonic flight speeds, represent a demanding compromise in desired engine characteristics.

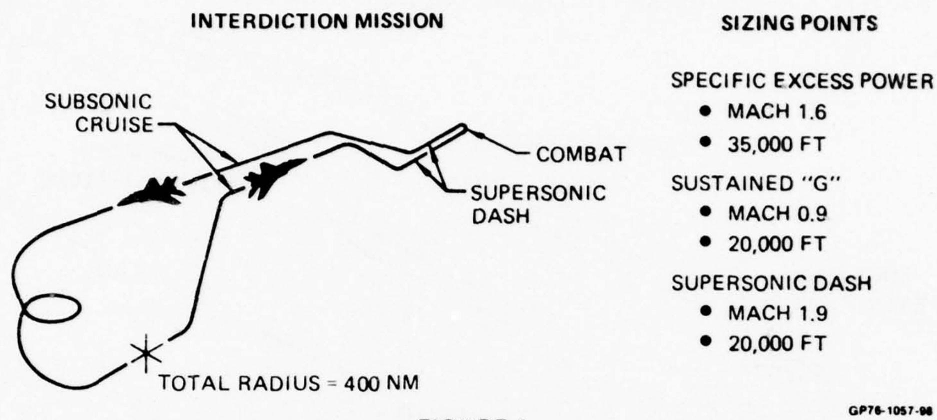

FIGURE 4
PHASE I DESIGN MISSION AND PERFORMANCE REQUIREMENTS

In Phase II, the thrust and fuel sizing elements of a strike mission were parametrically varied to provide increased capabilities for aircraft/requirement interaction evaluations. The fuel sizing variables included cruise radius and supersonic dash radius, Mach number, and altitude as shown in Figure 5. Thrust sizing was accomplished by variations in aircraft take off thrust-to-weight ratio with a specified minimum energy maneuverability requirement at the supersonic dash flight condition. Thus the Phase II aircraft represented in the correlation equations were not all required to be compatible with operation at the high dynamic pressure Phase I interdiction mission dash condition.

In both Phases, aircraft performance was computed and correlation equations were developed to permit evaluations of alternate and multi-mission systems. Three aircraft roles were used to provide a measure of operational flexibility. As shown in Figure 6, the Interdiction mission was one of six included in the Tactical Strike role. The role definitions included mission profiles and radii, performance requirements, and operational limits. For example, the mission radii requirements included in the Tactical Strike role are:

- Interdiction	- 400 nm
- Counter-Air	- 400
- Defense Suppression	- 700
- Close Air Support	- 100
- Lo-Level Reconnaissance	- 600
- Armed Reconnaissance	- 240

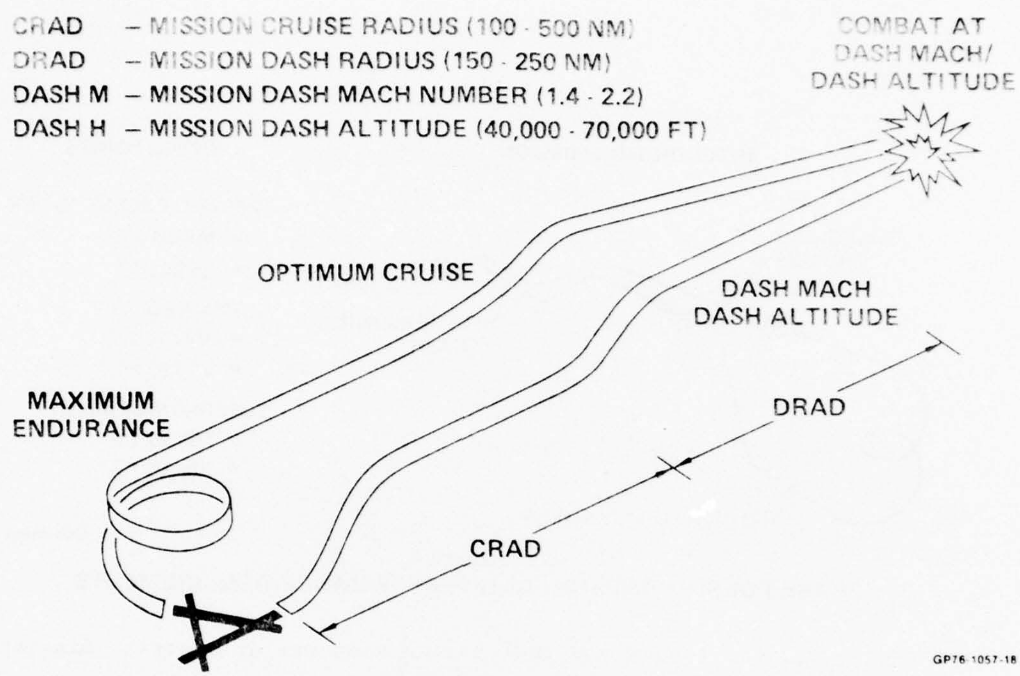

FIGURE 5
PARAMETRIC MISSION VARIABLES FOR CADE DATA GENERATION

ROLE	PHASE I	PHASE II
TACTICAL STRIKE ROLE	INTERDICTION COUNTER-AIR DEFENSE SUPPRESSION CLOSE AIR SUPPORT LO-LEVEL RECCE ARMED RECCE	INTERDICTION LO-LEVEL RECCE *PARAMETRIC DEEP STRIKE
AIR SUPERIORITY	AIR SUPERIORITY ESCORT FIGHTER SWEEP COMBAT AIR PATROL LO-LEVEL POINT INTER.	AIR SUPERIORITY COMBAT AIR PATROL LO-LEVEL POINT INTER.
INTERCEPTOR	HI-LEVEL POINT INTER. HI-LEVEL AREA INTER. LO-LEVEL AREA INTER. COMBAT AIR PATROL HI-LEVEL RECCE	HI-LEVEL POINT INTER. COMBAT AIR PATROL
		FERRY

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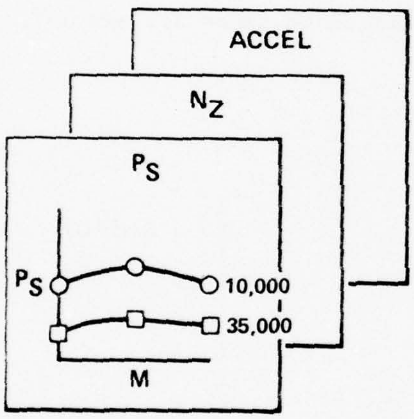
FIGURE 6
PROGRAM ROLES AND MISSIONS

The Tactical Strike role performance requirements are shown in Figure 7. In the Phase I evaluations, it was determined that the Interdiction and Lo-Level Reconnaissance missions represented the most demanding requirements. The remaining missions, which had no influence on the design selections or interaction evaluations, were excluded in Phase II.



- **SUSTAINED g AT**
  - 20,000 FT AT M = 0.9 .... 4.5 g
  - 30,000 FT AT M = 0.9 .... 3.0 g
- **INSTANTANEOUS g AT**
  - 30,000 FT AT M = 0.9 .... 4.5 g
  - 35,000 FT AT M = 1.6 .... 6.5 g
- **SPECIFIC EXCESS POWER AT**
  - 20,000 FT AT M = 0.9 AT 1 g .... 600 FPS
  - 20,000 FT AT M = 1.9 AT 1 g .... 800 FPS
  - 20,000 FT AT M = 1.9 AT 3 g .... 600 FPS
  - 30,000 FT AT M = 0.9 AT 1 g .... 400 FPS
  - 35,000 FT AT M = 1.6 AT 1 g .... 700 FPS
  - 35,000 FT AT M = 1.6 AT 3 g .... 100 FPS
- **TIME TO ACCELERATE**
  - FROM M = 0.9 TO M = 1.6 AT 35,000 FT ... 1 MIN

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FIGURE 7
TYPICAL PERFORMANCE REQUIREMENTS
TACTICAL STRIKE ROLE

In this program, the engine and requirement interaction evaluations conducted encompassed inordinately broad matrices of mission types, payloads, and aircraft component design variables. Further, the engine design concepts evaluated were defined with differing techniques and design duty cycles, thus, precluded comparative evaluations of a specific nature. Consequently, the approach selected was directed toward demonstration of the general applicability of the procedure, compatibility throughout the industry, and development of an initial data base for tactical aircraft applications.

3. FIGHTER ENGINE/AIRFRAME EVALUATION PROCEDURE

Comparisons of aircraft size, cost and operational characteristics provide a valid basis for engine and airframe design selections and trade-offs. However, such comparisons must be made using a systematic analysis procedure because of complex interactions. That procedure must account for, and identify, the relationships between engine and airframe design variables and aircraft size, mission, and performance characteristics.

During Phase I, MCAIR developed the Fighter Engine/Airframe Evaluation Procedure shown schematically in Figure 8. The development of this procedure was directed at obtaining a valid basis for engine/airframe design selection and aircraft/requirement trade-offs for future fighter aircraft programs. The procedure requires discrete inputs which are discussed in Section 3.1. The procedure computation and output are presented in Sections 3.2 and 3.3, respectively.

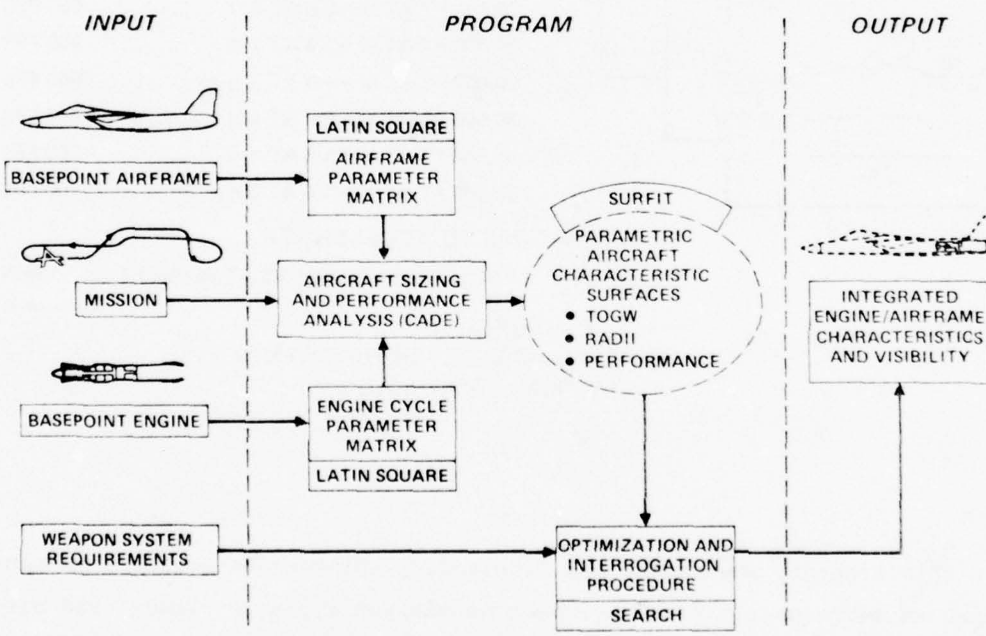

FIGURE 8
ENGINE/AIRFRAME EVALUATION PROCEDURE

3.1 Input

Three inputs are required to initiate the use of the Evaluation Procedure for engine/airframe design selection. In an aircraft development program, the USAF User Command makes the initial input by defining role requirements. This input consists of the desired mission and performance capabilities and operational limits. Typically, this could be a Required Operational Capability (ROC) document. Such a document would normally identify the desired aircraft IOC, maximum Mach number, and other key factors affecting the design. Then, the participating engine and airframe companies must identify design candidates which are compatible with the ROC, e.g., the engine and airframe component technology used must be consistent with the desired IOC. These selections are judgements, based on the technical expertise of the companies and the results of previous investigations of similar systems. The engine and airframe companies must also identify the engine and airframe design variables which could significantly affect the aircraft characteristics and the range of values over which each variable should be considered. For example, important airframe design variables could include wing loading, sweep, and aspect ratio; important engine design variables could include fan and overall cycle pressure ratio, bypass ratio, turbine inlet temperature, and engine control schedules and limits.

Consequently, three types of design inputs are required: (1) candidate engine and airframe designs, (2) identification of the important design variables of each candidate, and (3) the values over which the important variables should be evaluated to define an optimum aircraft system.

The impact of varying mission radius and performance requirements on aircraft TOGW and its design characteristics can be determined from the computed aircraft relationships. These requirements inputs can include any combination of mission radii or performance requirements, in terms of Ps, N_z, or acceleration times. A total of 17 requirements can be imposed simultaneously.

3.2 Computation

Relationships between the engine and airframe design variables and aircraft characteristics must be established to provide a meaningful basis for design selection. These relationships could be obtained by computing the size and performance of aircraft designs representing all combinations of the important engine and airframe design variables. However, the time and cost of such an approach would be impractical. A computational procedure has been developed which provides the relationships required for engine and airframe

design selection based on aircraft system characteristics. The following paragraphs briefly discuss each of the key computation elements of this procedure which are shown in Figure 8.

3.2.1 Aircraft Matrix Selection - A large number of engine and airframe design variables may be important in determining the aircraft size required to achieve mission and performance requirements. As the number of design variables is increased, the number of possible variable combinations (aircraft designs) also increases rapidly. If, for example, eleven design variables were considered and all variable combinations were analyzed, more than four million aircraft design computations would be required. We have employed a mathematical procedure called "Latin Square" to systematically select a manageable matrix of aircraft designs for analysis, Figure 9. The Latin Square procedure defines the minimum number of aircraft designs which encompass the entire range of all the important engine and airframe design variables. With eleven variables for example, the use of the Latin Square would require analysis of only about 250 aircraft designs. An example of the use of the Latin Square procedure to define an aircraft design matrix is presented in Appendix A.

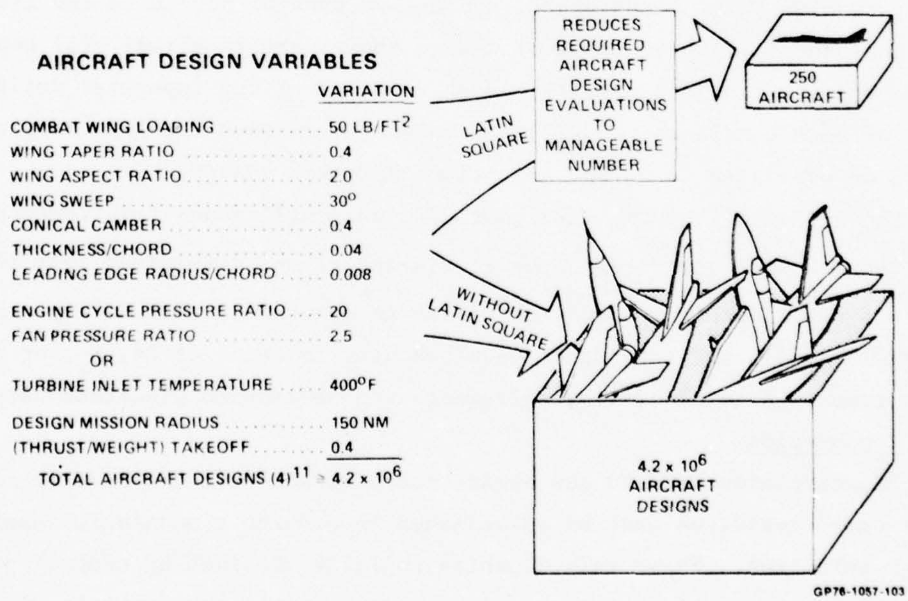

FIGURE 9
SELECTION OF AIRCRAFT DESIGN MATRIX (LATIN SQUARE)

3.2.2 Aircraft Design and Performance Analysis - The initial step in the determination of aircraft characteristics for the Latin Square design matrix is to define installed inlet/engine performance. The Latin Square matrix of aircraft encompass a parametric family of engine designs. The engine company defines the size, weight and performance characteristics of each engine in that parametric family, using the aircraft total pressure recovery, bleed, and power extraction. The Propulsion System Installed Performance (PSIP) computer program is used to compute the required inlet capture area, match inlet and engine airflows and compute inlet drag, Figure 10.

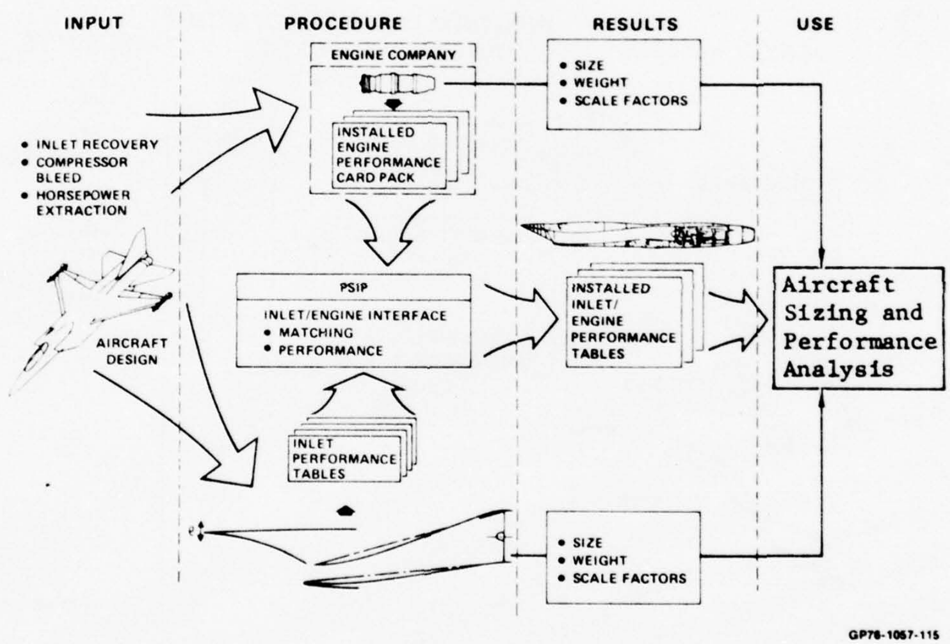

FIGURE 10
GENERATION OF PROPULSION SYSTEM INSTALLED PERFORMANCE

The size, weight, and scaling characteristics of both the engines and inlets and the installed inlet/engine performance data are input to the aircraft sizing and performance analysis.

Aircraft sizing and performance analyses are accomplished by scaling the components of an input aircraft design using a computer procedure called CADE, Computer Aided Design Evaluation, Figure 11. The initial step in this

procedure is to define the geometry, propulsion system, aerodynamic, and weight characteristics of the input aircraft design and the scaling characteristics of each major aircraft component. CADE is used to scale the weight and geometry of the input aircraft components to determine physical characteristics. Mission fuel, engine thrust, and configuration size are determined by simultaneously sizing the aircraft to achieve the required design mission radius, sea level static thrust to TOGW ratio, and static weight balance. The aircraft performance analyses include computation of alternate mission radii, performance at preselected flight conditions and engine power settings, and acceleration times with variations in external stores. Such computations are accomplished for each aircraft design in the Latin Square matrix.

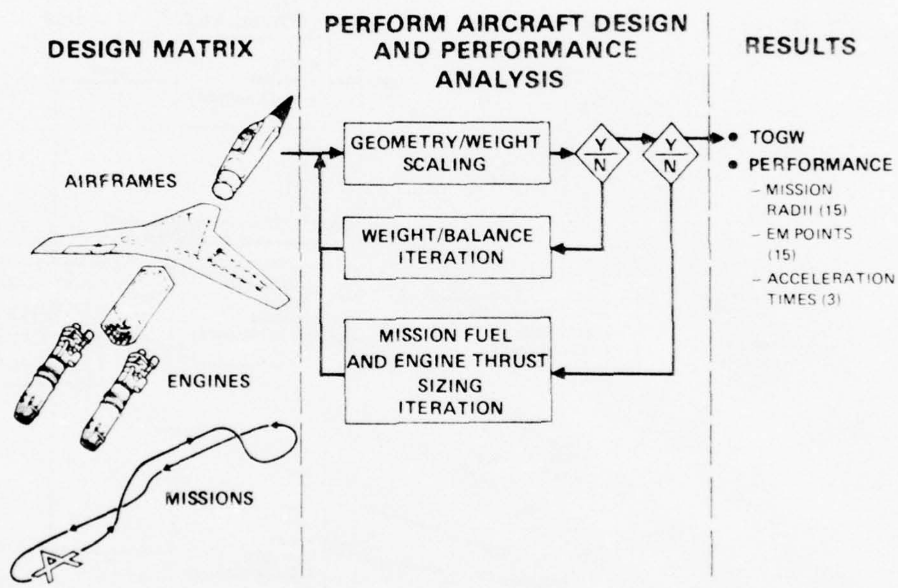

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FIGURE 11
DETERMINATION OF PARAMETRIC AIRCRAFT DESIGN CHARACTERISTICS (CADE)

3.2.3 Correlation of Aircraft Characteristics - A mathematical curve fit procedure (SURFIT) is used to define the relationships between the computed aircraft characteristics and the design variables. Each aircraft characteristic parameter defined in CADE is represented by a quadratic equation composed of the design variables as shown in Figure 12. The result, for eleven design variables, is an equation which represents an eleven dimensional mathe-

matical surface with 78 possible coefficients. A least squares curve fit of the computed aircraft characteristics is used to determine coefficient values for each term in the equation. Experience has shown that the aircraft characteristics, such as TOGW, can be accurately represented by 30 to 35 term equations, with the remaining coefficients set equal to zero. The correlation equations provide the relationships required for meaningful engine/airframe design selections. As shown in Figure 12, the equations can be used to define relationships between aircraft characteristics, such as TOGW, P_S, and N_Z, and the important design variables, such as T/W and W/S. Although only two design variables are shown in the example, such relationships can be obtained for any combination of the design variables considered. Consequently, the correlation equations provide the capability to compute aircraft weight, mission radii, and performance characteristics for any aircraft design encompassed by the Latin Square matrix.

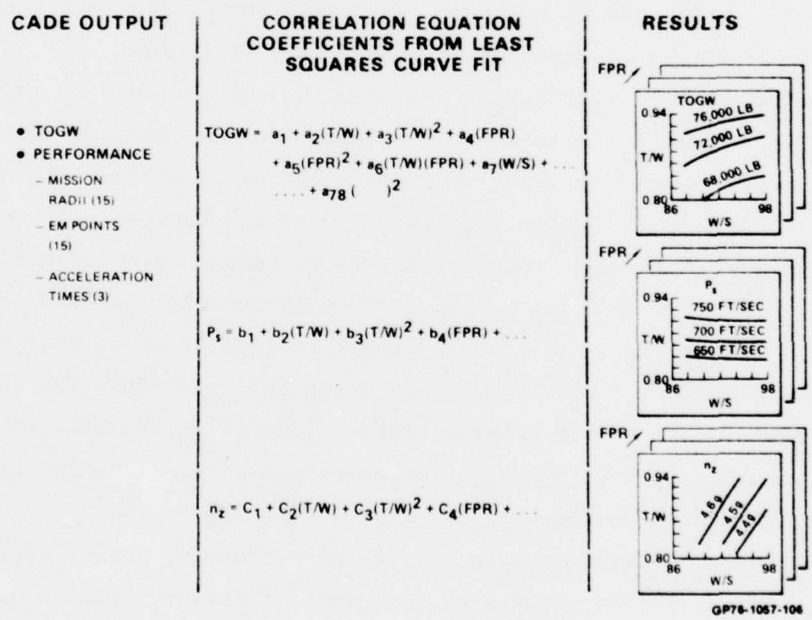

FIGURE 12
DEVELOPMENT OF MATHEMATICAL DESCRIPTION OF A COMPLETE CLASS OF FIGHTER AIRCRAFT

Nearly two hundred CADE output parameters were correlated in Phase I and more than 400 in Phase II using the SURFIT procedure. These include:

1. Take-off gross weight
2. Mission radii and performance parameter
3. Engine and airframe physical characteristics
4. Mission visibility - at each segment of the design mission (Phases I and II) and at each segment of two additional missions (Phase II),
   - flight conditions
   - fuel used
   - engine operating characteristics
   - installation losses

The mission radii and performance relationships provide a quantitative basis for size and flexibility trade-offs. The mission segment relationships provide visibility into propulsion system/airframe interactions to a degree which has not previously been possible.

3.2.4 Aircraft Optimization - The minimum TOGW aircraft design capable of achieving specified mission radius and performance requirements is identified by means of an optimization procedure called SEARCH. This procedure utilizes the correlation equations to describe the variations of aircraft weight and performance parameters as functions of the design variables.

It was shown in Figure 12 that the equations can be used to define variations in TOGW, P_s and N_z as three design variables are changed. The optimization procedure is illustrated by superimposing those relationships, Figure 13. The interactions between the design variables, TOGW, and the two performance parameters are clearly defined. For performance requirements corresponding to P_s = 700 ft/sec and N_z = 4.5 g's, the minimum achievable TOGW and corresponding design variables can be quickly determined. In this example, only two design variables were permitted to change. Repeating this procedure for an additional design variable, such as fan pressure ratio, identifies the minimum TOGW aircraft for three variables. This optimization procedure considers up to eleven design variables simultaneously.

The SEARCH computer program is capable of performing optimizations using any of the surface fit parameters as the payoff function, with 11 design variables and up to 17 specified mission radius and performance requirements. Development of this optimization technique was based on Box's "Complex Method," Reference 6. Using this procedure, it is possible to rapidly and inexpensively establish the interactions between mission radius and performance requirements, TOGW, and the engine and airframe design variables.

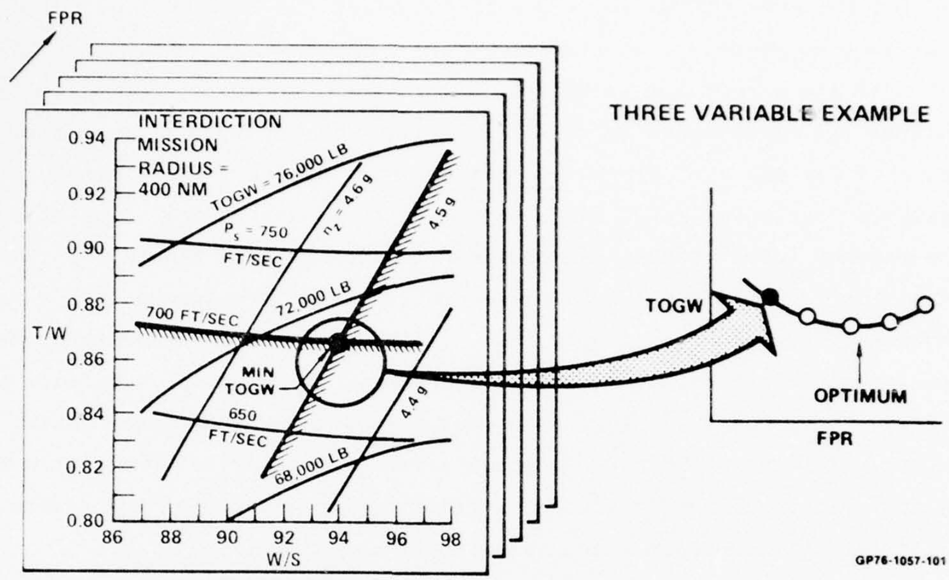

FIGURE 13
TOGW OPTIMIZATION AS A FUNCTION OF DESIGN VARIABLES AND PERFORMANCE REQUIREMENTS (SEARCH)

3.3 Output

The output from the Fighter Engine/Airframe Evaluation Procedure includes the correlation equations and, for each SEARCH optimization, a description of the geometry and performance characteristics of the selected aircraft. The correlation equations are retained and can be repeatedly used to define and evaluate interactions between the design variables and system requirements. For each aircraft defined using the SEARCH optimization procedure, the design variables are identified, and the engine and airframe geometry can be obtained from the correlation equations. Using those design variables, any mission radius or performance parameter for which correlation equations were developed can be determined. Finally, at each segment of the design mission, the fuel used, inlet and nozzle geometry, and installation losses can also be determined.

A procedure has been defined to use the correlation equations to assess relative aircraft operational flexibility. A quantitative measure of the capability of an aircraft to achieve mission, role, or multi-role radius and performance requirements provides the basis for such assessments. We call this parameter a merit rating and briefly describe its determination in the following paragraphs.

The development of mission merit ratings is illustrated in Figure 14. The initial step in the procedure is to define the mission requirements and to rank them by relative importance. Each requirement is then quantitatively weighted, with the sum of the weighting factors equal to unity. Requirement merit ratings are established by determining the maximum and minimum performance levels computed for any aircraft in the Latin Square matrix. The minimum level is assigned a value of zero, the required level is assigned a value of one, and the maximum level attained is assigned a value of two, Figure 14. Consequently, an aircraft design with performance exceeding the requirement has a requirement merit rating greater than unity and, conversely, one which does not meet the requirement has a rating of less than unity. To determine a mission merit rating, the product of requirement merit rating and importance factor is determined. The sum of the weighted merit ratings is defined as the mission merit rating, and can be used as a quantitative measure of the aircraft capability to perform the mission requirements.

REQUIREMENTS	MERIT RATING	×	IMPORTANCE FACTOR	=	WEIGHTED MERIT RATING
P_s	1.25		0.15		0.188
RADIUS	–		–		–
n_z	–		–		–
V_{MAX}	–		–		–
t ACCEL	–		–		–
			$\Sigma = 1.0$		Σ = MISSION MERIT RATING

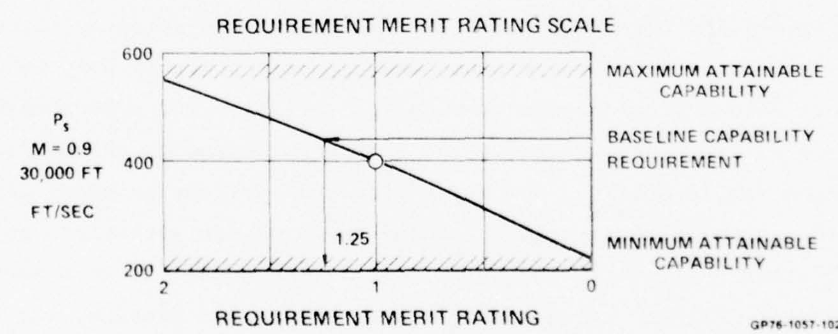

FIGURE 14
DEFINITION OF MISSION MERIT RATING

The merit ratings are used to provide a measure of aircraft capability to perform individual missions, multi-mission roles, and multiple roles, Figure 15. MCAIR has incorporated importance factors which reflect our own opinion. We have, however, provided each individual user the capability to alter these judgements,

reorder the weighted parameters, and assign quantitative importance factors which properly reflect his personal judgement of priorities.

MISSION CAPABILITY

REQUIREMENTS MERIT RATING x IMPORTANCE FACTOR = WEIGHTED REQ'T MERIT RATING

P_s

RADIUS

n_z

Σ = MISSION MERIT RATING

MULTI-MISSION CAPABILITY

MISSIONS MERIT RATING x IMPORTANCE FACTOR = WEIGHTED MISSION MERIT RATING

INTERDICTION

Σ = ROLE MERIT RATING

MULTI-ROLE CAPABILITY

ROLES MERIT RATING x IMPORTANCE FACTOR = WEIGHTED ROLE MERIT RATING

TACTICAL STRIKE

Σ = MULTI-ROLE MERIT RATING

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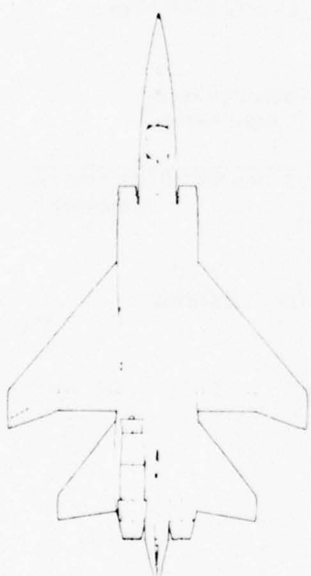
FIGURE 15
MERIT RATING PROVIDES A MEASURE OF FLEXIBILITY

4. PHASE I ENGINE/AIRCRAFT EVALUATIONS - FIXED CYCLE ENGINES

Aircraft characteristics data correlations were developed to provide a data base of aircraft/requirement interactions with fixed cycle engines. The Fighter Engine/Airframe Evaluation Procedure was also used to select a turbofan-powered aircraft design, which was then validated by design layout and performance analyses. The following sections briefly describe the design variables considered, an example of requirements/aircraft interactions, and the validation of aircraft designs selected using the procedure.

4.1 Aircraft Design Variables

A wide range of airframe, sizing, and engine design variables was considered in Phase I to demonstrate the flexibility of the Fighter/Airframe Evaluation Procedure. Seven wing design and two engine/airframe sizing variables were considered. These variables and their corresponding ranges of values are shown in Figure 16.



ENGINE/AIRFRAME SIZE

- TAKEOFF THRUST/WEIGHT RATIO (T/W) = 0.6 – 1.0
- INTERDICTION MISSION RADIUS = 350 – 500 NM

WING DESIGN

- COMBAT WING LOADING $(W/S)_{co}$ = 50 – 100 LB/FT^2
- WING TAPER RATIO (λ) = 0.1 – 0.4
- WING ASPECT RATIO (AR) = 2 – 4
- WING LEADING EDGE SWEEP $(\Lambda)_{LE}$ = 30° – 60°
- WING CONICAL CAMBER (C_{L_d}) = 0 – 0.4
- WING THICKNESS/CHORD RATIO $(t/c)_R$ = 0.04 – 0.08
- WING LEADING EDGE RADIUS TO CHORD RATIO (LER/$\bar{C}$) = 0.001 – 0.008

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FIGURE 16
WING DESIGN AND ENGINE/AIRFRAME SIZING VARIABLES

General Electric provided parametric families of both turbojet and mixed flow turbofan engine designs. The design variables of the twelve turbojets and nine turbofans are shown in Figure 17. The selection of the design variables and a control schedule establish engine weight and performance characteristics. For example, engine thrust to weight relationships are shown in Figure 18 for both the turbofans and turbojets. Typically, thrust-to-weight ratio varies from about 7 to 9.5 for these engines at sea level static maximum augmented power conditions. Installed fuel consumption (SFC) characteristics and thrust variations versus Mach number are shown in Figures 19 and 20 for the turbofans and turbojets respectively. Maximum power SFC is shown at Mach 1.9, 20,000 ft. altitude, corresponding to the Interdiction Mission dash condition. Typically, SFC varies from about 2.1 to 2.7 for the turbofans and from about 1.9 to 2.1 for the turbojets at this operating condition. Intermediate power SFC at a typical cruise condition ranges from about 0.8 to 1.1 for the turbofans and from 1.05 to 1.25 for the turbojets.

Turbojets GE16/J2-A1 Through A-12

OPR \ T.I.T. - °F	2400	2600	2800
12	1	2	3
16	4	5	6
20	7	8	9
24	10	11	12

Turbofans GE16/F8-A13 Through A-21

OPR \ FPR / BPR	2.2 / 3	3.45 / 1	4.70 / 0.3
20	13	14	15
26	16	17	18
32	19	20	21

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FIGURE 17
PARAMETRIC ENGINE DESIGNS

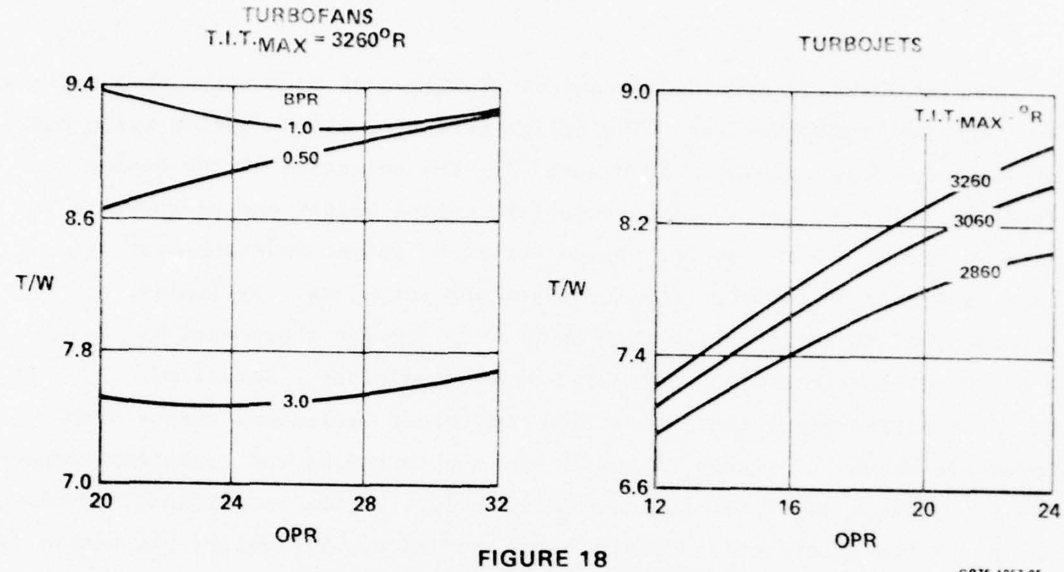


FIGURE 18
UNINSTALLED ENGINE CHARACTERISTICS
SEA LEVEL STATIC, MAXIMUM AFTERBURNER

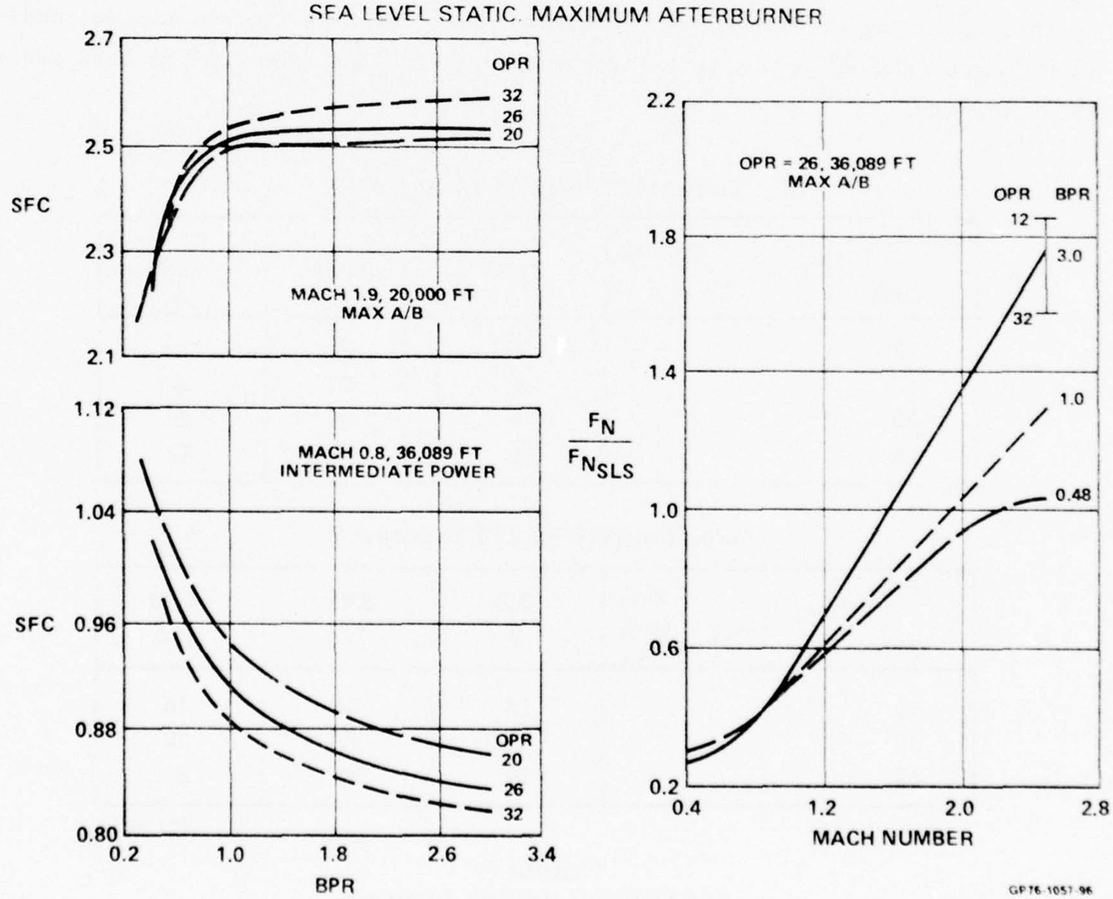


FIGURE 19
GE TURBOFAN PERFORMANCE CHARACTERISTICS

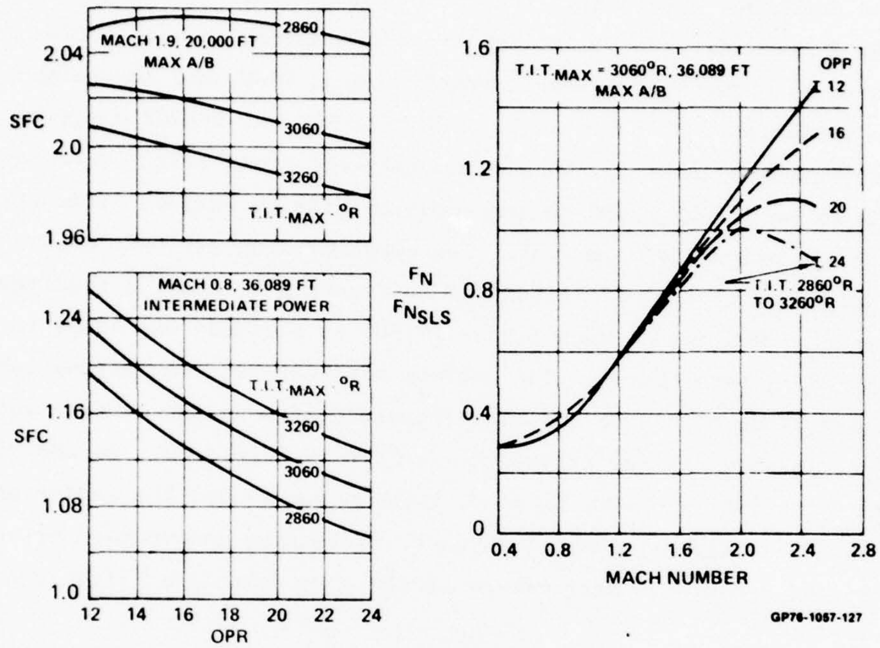


FIGURE 20
GE TURBOJET PERFORMANCE CHARACTERISTICS

The ratio of engine thrust at Mach and altitude flight conditions to thrust at sea level static conditions characterizes the potential impact of design and schedule variables on engine sizing. This ratio is shown for the turbofans and turbojets in Figures 19 and 20 respectively at a constant altitude of 36,089 ft. At Mach 2.5, this thrust ratio varies from about 1.0 to 1.8 for the turbofans and from 0.9 to 1.5 for the turbojets. Variation of turbofan overall cycle pressure ratio from 20 to 32 causes a change in thrust ratio of about 0.25 at Mach 2.5, but is negligible at subsonic flight conditions. Varying turbojet turbine inlet temperature has a negligible effect on this augmented powered thrust ratio at all flight speeds.

Aircraft lift, drag, and fuel volume characteristics are also affected by the airframe design variables. Consequently, combining engine and airframe design variables describes substantially different aircraft designs for consideration in selecting designs for specified mission and performance requirements. The Latin Square procedure was used to define a matrix of approximately 250 airframe/engine designs for both the GE turbofan and turbojet engines.

4.2 Requirement/Aircraft Interactions

As described previously, the correlation equations developed with the Fighter Engine/Airframe Evaluation Procedure permit identification of the interactions between performance requirements, TOGW, and engine and airframe design variables. In the example of Figure 21, the SEARCH optimization procedure was used to identify the minimum take-off gross weight turbofan aircraft capable of achieving a 400 nm Interdiction Mission radius. This aircraft weighed approximately 55,000 lb. The corresponding aircraft design variables are designated by the circle symbols in Figure 22. Next, a requirement to achieve P_s = 800 fps at Mach 1.9 at 20,000 ft altitude was added to the initial 400 nm radius requirement. The minimum aircraft TOGW satisfying both requirements was about 62,000 lb and the aircraft design variables were substantially changed, as shown by the triangular symbols in Figure 22. As additional performance requirements were imposed, TOGW increased and the engine and airframe design variables changed still further, reflecting compromises between aerodynamic and propulsive performance at the most demanding flight conditions.

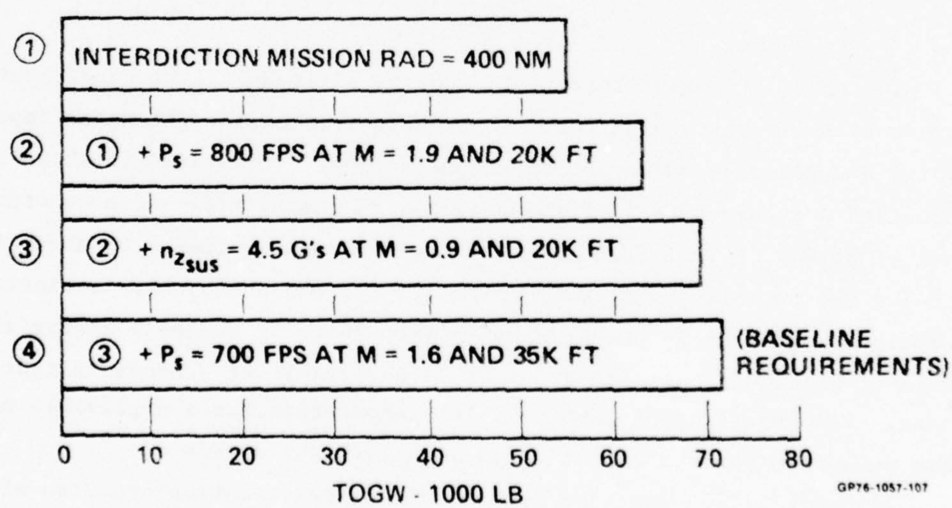


FIGURE 21
IMPACT OF ADDING REQUIREMENTS ON TOGW

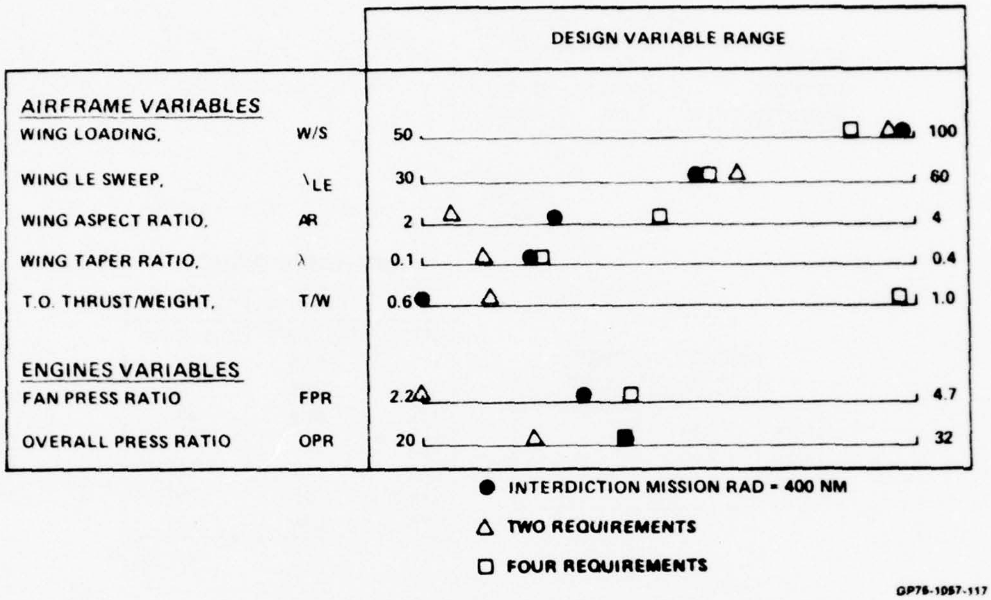


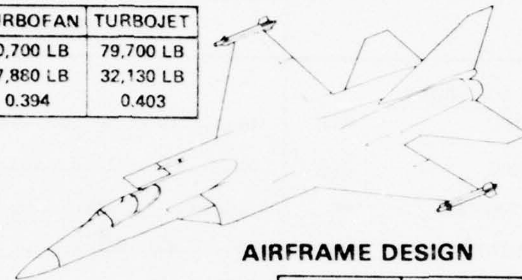
FIGURE 22
IMPACT OF REQUIREMENTS ON DESIGN VARIABLES

4.3 Aircraft Design Evaluation and Validation

The selected aircraft was required to achieve all 17 of the Tactical Strike Role mission and performance requirements, described in Section 2. The minimum TOGW aircraft designs capable of achieving those requirements with turbojet and turbofan engines are shown in Figure 23. On the basis of its lower TOGW, the turbofan aircraft was selected for design verification. The CADE program was then used to verify the aircraft TOGW and performance obtained from the correlation equations. A design layout was used to verify the aircraft geometry, fuel volume, and component integration. The results of this verification, shown in Figure 24, demonstrate the capability to accurately correlate aircraft characteristics from a Latin Square matrix of designs and to determine realistic aircraft performance and designs from those correlations.

Life cycle costs were computed for the selected aircraft using the MCAIR Advanced Design Life Cycle Cost Model. The breakdown of the estimated life cycle costs is shown in Figure 24.

	TURBOFAN	TURBOJET
TOGW	70,700 LB	79,700 LB
INT FUEL	27,880 LB	32,130 LB
FUEL FRACTION	0.394	0.403



AIRFRAME DESIGN

	TURBOFAN	TURBOJET
$(W/S)_{co}$	93.5 LB/FT^2	91.5 LB/FT^2
λ	0.18	0.20
AR	2.97	3.15
Λ_{LE}	47.5	46
C_{L_d}	0.4	0.4
(t/c)	0.04	0.04
LER/C	0.001	0.0016
$(T/W)_{to}$	0.98	0.94

ENGINE DESIGN

	TURBOFAN	TURBOJET
FPR	3.30	–
OPR	25.0	21.2
TIT	2800°F	2400°F

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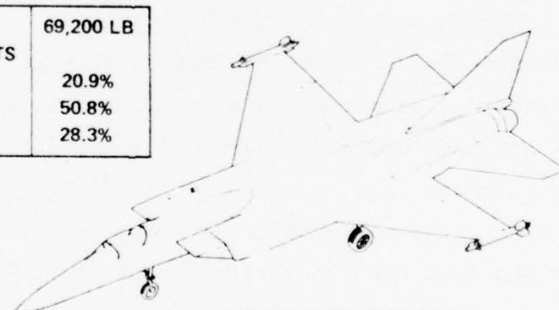
FIGURE 23
PHASE I OPTIMIZATION RESULTS

TOGW	69,200 LB
LIFE CYCLE COSTS	
RDT&E	20.9%
INVESTMENT	50.8%
O&M	28.3%



AIRFRAME DESIGN

$(W/S)_{co}$	94.0 LB/FT^2
λ	0.176
AR	2.92
Λ_{LE}	47.1°
C_{L_d}	0.4
(t/c)	0.04
LER/C	0.001

TURBOFAN ENGINE DESIGN

FPR	3.45
OPR	26.0
TIT	2800°F

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FIGURE 24
BASELINE AIRCRAFT CHARACTERISTICS

Mission, role, and multi-role merit ratings were also computed for the selected aircraft, using the procedures described previously. These merit ratings, as shown in Figure 25, provide a quantitative basis for evaluating the impact at engine and/or airframe design variable changes on aircraft operational flexibility.

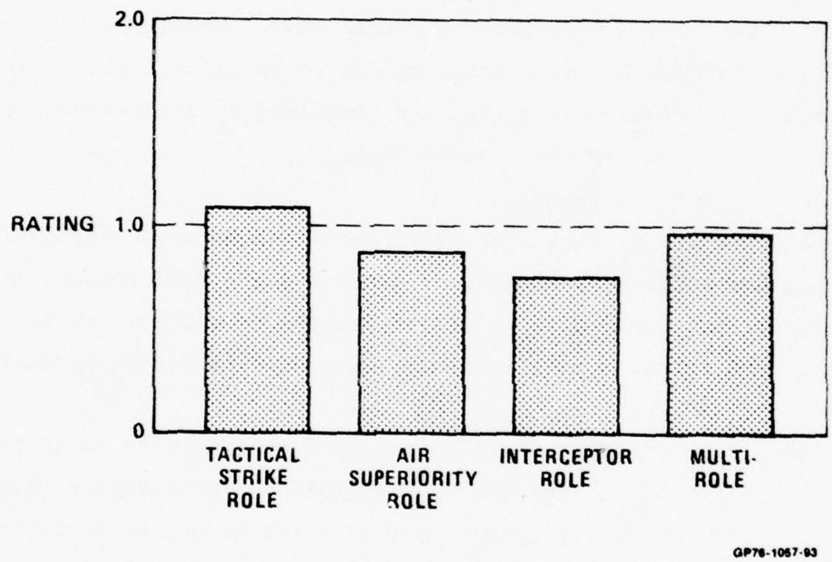

FIGURE 25
AIRCRAFT OPERATIONAL FLEXIBILITY RATING

5. PHASE II ENGINE/AIRCRAFT EVALUATIONS - VARIABLE GEOMETRY TURBINE ENGINES

A data base of parametric aircraft characteristics has been developed for two variable geometry turbine turbojet engine design concepts. Improved data generation and correlation procedures produced significantly increased capabilities for evaluating design and alternate mission and performance requirement interactions. The following paragraphs summarize the parametric data development procedures and the results obtained from evaluations of Detroit Diesel Allison (DDA) and Pratt and Whitney Aircraft Co. (P&WA) engine designs. The component technology used to define the DDA and P&WA engines is very advanced and highly competitive at this time. Consequently, quantitative engine and aircraft system data which relate to specific engine characteristics are not included in this report, but are contained in References 2 and 3 which are proprietary to DDA and P&WA respectively.

5.1 Parametric Data Development

Parametric aircraft characteristics correlations were developed using VGT turbojet engines defined by DDA and by AFAPL using a P&WA parametric engine design computer program. Wide ranges of engine and airframe design, aircraft fuel sizing, and thrust sizing variables were used to define parametric families of aircraft.

The results obtained in Phase I indicated that only three of the seven airframe design variables impacted the aircraft characteristics to a significant degree. Consequently, the number of airframe design variables used in Phase II was reduced from seven to three as shown in Figure 26. The total number of independent variables was maintained at eleven by increasing the number of fuel sizing variables from one to four and adding an engine airflow schedule parameter. The four selected fuel sizing parameters permit independent variations in the required cruise and dash fuel within a consistently defined mission description. The subsonic cruise radius was used in both Phases I and II for fuel sizing and is performed at the optimum Mach number and altitude for each engine/airframe design combination. The Phase I dash was fixed at 50 nm radius at Mach 1.9 and 20,000 feet altitude. In Phase II, however, supersonic dash radius, Mach number, and altitude were also used as variables for fuel sizing. Consequently, the Phase II parametric aircraft data include designs which are compatible with the extensive supersonic dash envelope shown in Figure 27, rather than the single dash condition considered in Phase I.

PARAMETERS		PHASE I	PHASE II	
• **ENGINE DESIGN (TURBOJETS)**		GE	P&WA	DDA
TURBINE INLET TEMPERATURE	(°F)	2400-2800	2600-3200	2350-3400
OVERALL PRESSURE RATIO		12-24	10-25	9-18
AIRFLOW SCHEDULE		–	ASP 0-1	θ_B = 1-1.36
• **AIRFRAME DESIGN**				
COMBAT WING LOADING	(LB/FT^2)	50-100	52-112	
SWEEP		30-60	40-60	
ASPECT RATIO		2-4	2-4	
CONICAL CAMBER		0 - 0.4	0.4	
THICKNESS/CHORD		0.04 - 0.08	0.04	
LEADING EDGE RADIUS/CHORD		0.001 - 0.008	0.001	
TAPER RATIO		0.1 - 0.4	0.176	
• **FUEL SIZING**				
CLIMB + CRUISE RADIUS	(NM)	300-450	100-500	
DASH MACH NO.	(M)	1.9	1.4-2.2	
DASH ALTITUDE	(1000 FT)	20	40-70	
DASH RADIUS	(NM)	50	150-250	
• **THRUST SIZING**				
UNINSTALLED FN SLS/TOGW		0.6-1	0.5-1.1	
P_s AT DASH MACH/ALTITUDE	(FT/SEC)	–	>0	

FIGURE 26
PARAMETRIC VARIABLES

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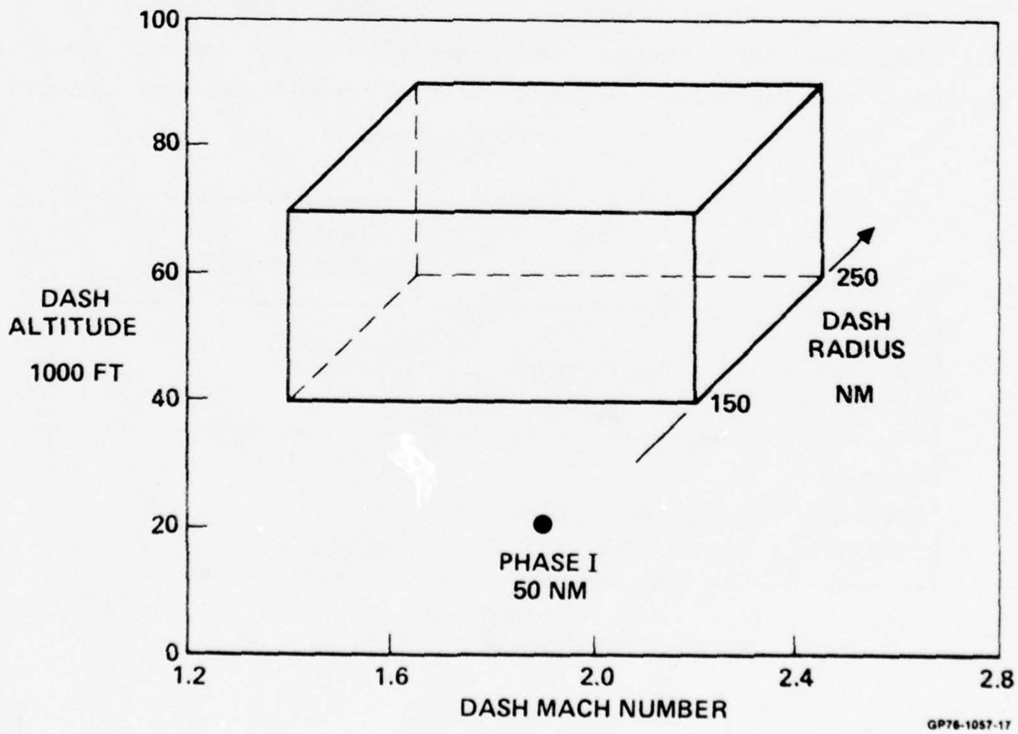

FIGURE 27
RANGE OF PARAMETRIC MISSION DASH VARIABLES

A parametric matrix of designs was defined for both the DDA and P&WA engine concepts using cycle design parameters and an airflow schedule parameter as independent design variables. The variables used to define the Phase I and II engines are compared in Figure 28. The airflow schedule parameter (identified as θ_{Break} for the DDA engines and as ASP for the P&WA designs) provides a large engine thrust lapse envelope with Mach number, as shown in Figure 29, and thus adds a degree of freedom in engine selections for various mission and performance requirements. The variable geometry turbines are used to produce large airflow variations at supersonic flight conditions without the subsonic, maximum power thrust penalties encountered in fixed cycle engines. In addition, engine airflow decay is minimized at reduced power subsonic cruise and loiter flight conditions. As a result, improvements in both internal cycle performance and installation losses are achieved.

The DDA matrix of 64 designs was defined by dividing the range of values of the three design variable into 4 equally spaced increments and generating an engine for each combination of those values; $(4)^3 = 64$. AFAPL used an 11 variable Latin Square array, as discussed in Section 3, to define the 121 designs used for the P&WA engines. Each set of designs was incorporated into a design matrix and aircraft size and performance characteristics were computed. For each aircraft, the fuel capacity was established by the parametric mission cruise and dash variables. Once each aircraft was defined, its specific excess power, load factor, and alternate mission capabilities were computed.

	OPR	TIT (^oF)	BPR	AIRFLOW SCHEDULING	NUMBER OF ENGINES
PHASE I					
GE FCE TJ	12 - 24	2400 - 2800	–	–	12
GE FCE TF	20 - 32	2800	0-3.0	–	9
PHASE II					
P&WA VGT TJ	10 - 25	2600 - 3200	–	ASP = 0 - 1.0	121
DDA VGT TJ	9 - 18	2350 - 3400	–	θ_B = 1.0 - 1.36	64

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FIGURE 28
PARAMETRIC ENGINE CHARACTERISTICS

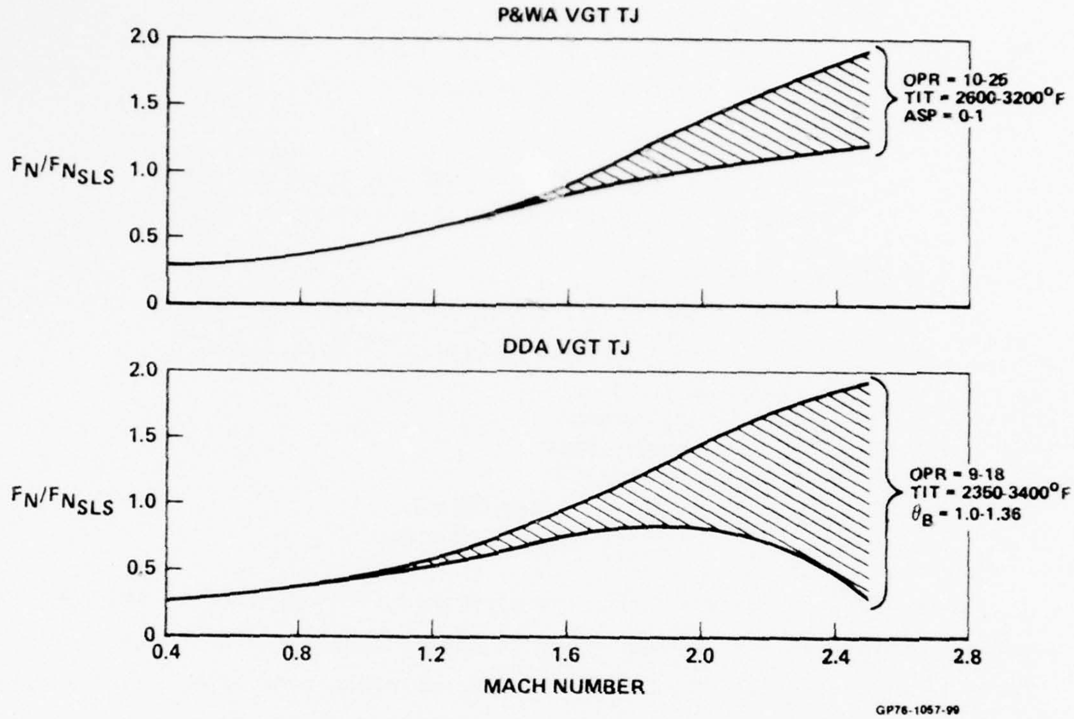

FIGURE 29
THRUST LAPSE COMPARISONS
36,089 FT ALTITUDE

The weight and performance characteristics of an aircraft configuration are functions of its engine and wing design parameters, engine thrust, and fuel capacity. Thus, weight and performance data can be analytically correlated using these parameters as independent variables as shown in Figure 30. The same equation format is used to correlate data for missions with fixed profiles and predetermined segment flight conditions, e.g., the alternate missions described in Section 2 and in Reference 1. The dash radius of the parametric strike mission, however, is strongly dependent on aircraft fuel, cruise radius and the Mach number and altitude at which the dash is performed. Consequently, aircraft fuel weight, cruise radius, and dash Mach number and altitude are all used as independent variables in the equations correlating data related to the parametric strike mission.

AIRCRAFT TOGW = FUEL WEIGHT + ZERO FUEL WEIGHT (ZFW)

– $ZFW = f\,[\underbrace{OPR, TIT, ASP}_{ENGINE};\ \underbrace{W/S, AR, \Lambda}_{AIRFRAME};\ \underbrace{FUEL, T/W}_{SIZING}]$

FUEL USED AS INDEPENDENT VARIABLE

ALTERNATE MISSIONS

– $RAD_{INTERDICTION} = f\,[\underbrace{OPR, TIT, ASP}; \underbrace{W/S, AR, \Lambda}; \underbrace{FUEL, T/W}]$

SAME FOR P_s, n_z, MISSION SEGMENT, AND VISIBILITY PARAMETERS

PARAMETRIC MISSION

– $DRAD = f\,[\underbrace{OPR, TIT, ASP}; \underbrace{W/S, AR, \Lambda}; \underbrace{FUEL, CRAD, M_D, H_D, T/W}]$

SAME FOR ALL PARAMETERS RELATED TO M_D AND H_D

DRAD = DASH RADIUS

CRAD = CRUISE RADIUS

M_D = DASH MACH NUMBER

H_D = DASH ALTITUDE

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FIGURE 30
SURFACE FITS

Over 400 data correlations were generated for both the DDA and P&WA engine-powered designs. In addition to the data obtained in Phase I, the Phase II data correlations include engine operating conditions, aerodynamic performance and installation losses for each segment of the parametric strike, interdiction, and lo-level reconnaissance missions and at 5 energy maneuverability flight conditions.

5.2 Summary of Results

Two separate evaluations were conducted, one using the Tactical Strike Role mission and performance requirements defined in Phase I to assess engine/airframe interactions, and the second using the parametric strike mission to assess the impact of aircraft mission and performance. Using the DDA and P&WA engine powered aircraft data correlations, aircraft designs were optimized for the Tactical Strike Role requirements described in Section 3. Those designs were used to assess TOGW sensitivities to engine and airframe design parameters and to variations of performance requirements. As a result of these investigations, it was determined that the use of variable geometry turbines and airflow scheduling in turbojet engines significantly reduces TOGW sensitivity to design variable changes.

Engines have been used from three different manufacturers. Consequently, variations in design practice, design duty cycle and engine complexity preclude meaningful comparisons of actual TOGW. Figure 31 shows an example of the

relative TOGW variation for the Phase I and Phase II turbojet-powered aircraft versus overall cycle pressure ratio increments from the optimum. At every point on these curves, the airframe and other engine design variables have been optimized to achieve the minimum TOGW aircraft which achieves the Tactical Strike Role requirements. Converged designs, i.e. those capable of achieving the specified role requirements, could be obtained only within a very limited OPR range with the GE fixed cycle/schedule turbojets used in Phase I. In contrast, both VGT turbojet concepts, with variations in airflow schedule incorporated into the data correlations, yielded converged designs throughout their design OPR range. Further, the sensitivity of TOGW to off-optimum values of OPR was far less for the VGT turbojet powered aircraft than for the fixed cycle turbojet powered aircraft. References 2 and 3 present extensive evaluations of the factors affecting the optimum design selection and the reduced sensitivities produced by the VGT turbojet powered systems.

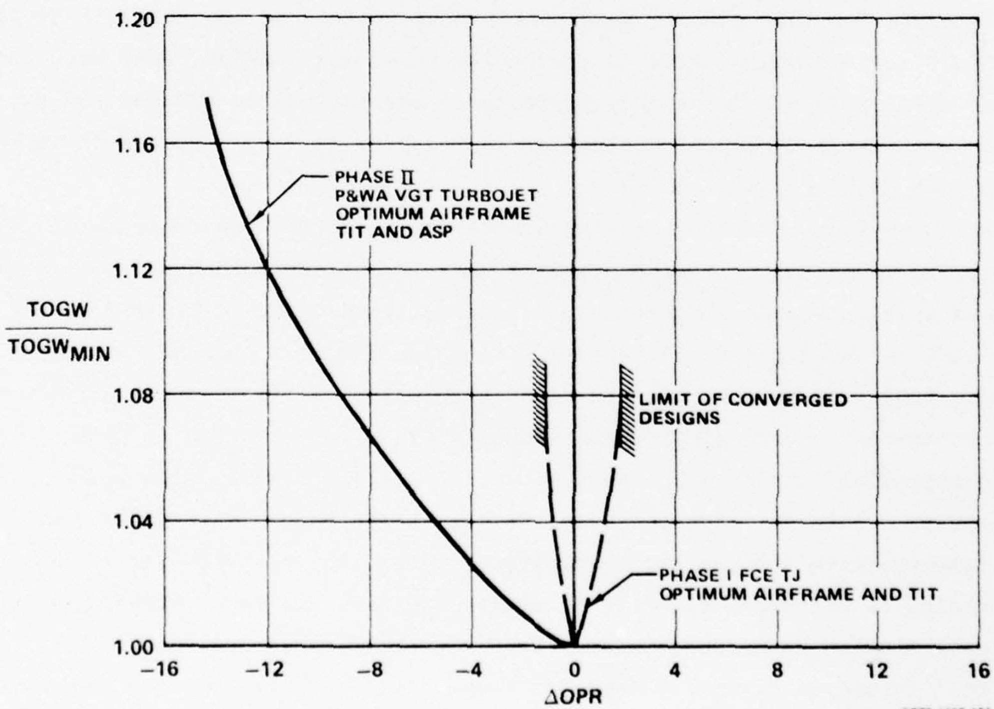

FIGURE 31
RELATIVE TOGW VARIATION FOR TACTICAL STRIKE AIRCRAFT

Aircraft/requirement interaction investigations were conducted using both the DDA and P&WA engine-powered aircraft data correlations. The objective of these investigations was to identify the effects of variations in thrust sizing and fuel sizing requirements on engine and airframe design parameters, aircraft maneuverability, and alternate mission performance capabilities. The aircraft characteristics data correlations obtained in this program afford unique capabilities to perform such investigations rapidly and inexpensively. To provide an example of this capability, interactions of strike mission cruise and dash radii were defined for a 1.6 dash Mach number and minimal maneuverability requirements. The results, shown in Figures 32, 33, and 34, can be used to estimate, for any desired combination of cruise and dash radius, aircraft TOGW, optimized design parameters, performance capability and alternate mission radii. The "map" format used to present the results of this evaluation can be used to relate interactions for any two selected fuel sizing parameters, e.g., strike mission cruise vs dash radii, interdiction mission radius vs. air superiority mission radius. In addition, thrust sizing requirements, such as subsonic vs supersonic maneuverability can be related using similar "map" formats.

The data for this example were obtained by optimizing the aircraft design to produce maximum dash radius at all cruise radii and TOGW's. Dash Mach number was set equal to 1.6 and the only performance constraints considered for this example were minimum required values of load factor (1.2 "g") and Ps (5 ft/sec) at the Dash Mach and altitude.

As shown in Figure 32, the aircraft design selection was dominated by fuel sizing, i.e., neither of the constrained maneuverability parameters encountered its minimum requirement. Consequently, the optimum engine cycle (OPR = 25 and TIT = 2600°F) is at design variable limits which minimize subsonic cruise specific fuel consumption. In addition, the optimum airflow schedule (ASP = 1) produces maximum engine airflow and, thus, minimum augmentation at dash thrust. The optimum wing loading was near the maximum available which also reduces drag at the dash condition. Consequently, optimum performance is obtained for these requirements, with a fixed engine/airframe design, but with T/W increasing as dash radius is increased relative to cruise radius. The maneuverability and alternate mission radii performance capabilities of these designs are shown in the "map" format in Figures 33 and 34, respectively. These maps can be used to (1) assess cruise vs dash radius requirements, (2) select optimum design variables, and (3) determine maneuverability and alternate mission radius performance capabilities.

REQUIREMENTS

DASH MACH	=	1.6
N_{zs} (DASH M&H)	>	1.2 g
P_s (DASH M & H)	>	5 fps

OPTIMIZED VARIABLES

OPR	-	CONSTANT (25)
ASP	-	CONSTANT (1.0)
TIT	-	CONSTANT (2,600)
W/S	-	103-110
AR	-	2.8-2.9
Λ	-	43-46.5
DASH ALT	-	43,000-46,000

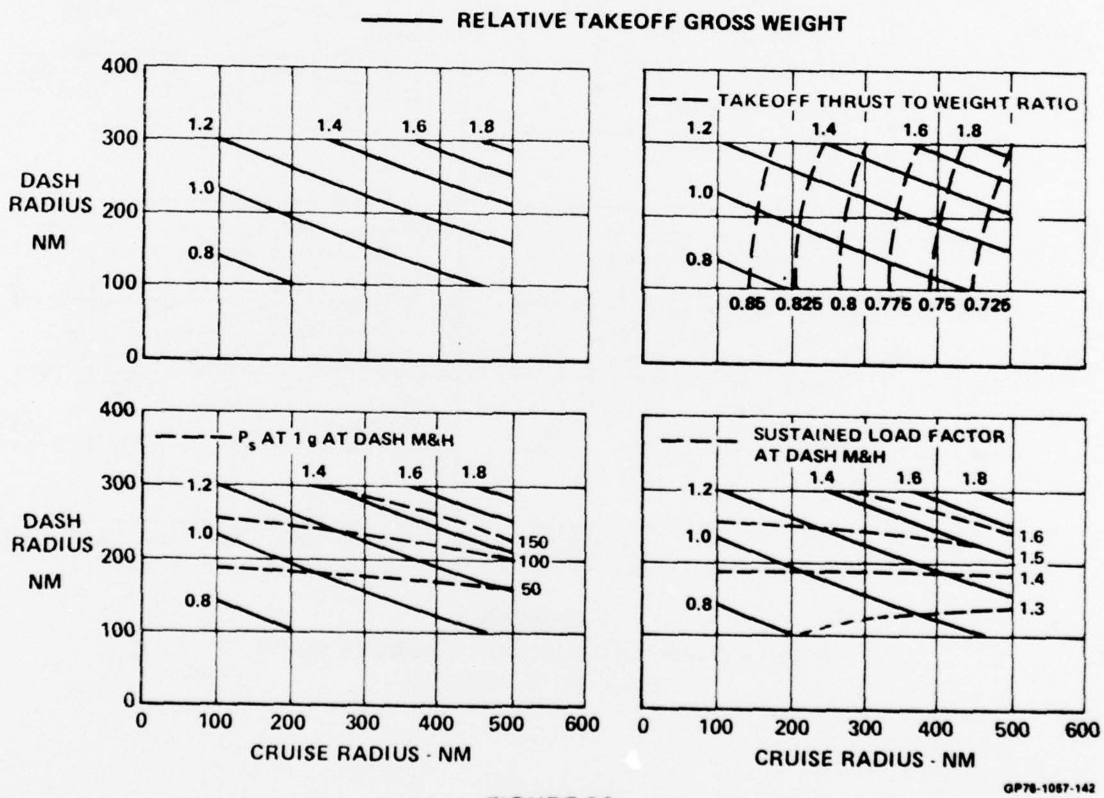

FIGURE 32
REQUIREMENT INTERACTION VISIBILITY MAPS
SIZING PARAMETERS P&WA VGT TURBOJETS

REQUIREMENTS		
DASH MACH	=	1.6
N_{zs} (DASH M&H)	>	1.2 g
P_s (DASH M & H)	>	5 fps

OPTIMIZED VARIABLES		
OPR	-	CONSTANT (25)
ASP	-	CONSTANT (1.0)
TIT	-	CONSTANT (2,600)
W/S	-	103-110
AR	-	2.8-2.9
Λ	-	43-46.5
DASH ALT	-	43,000-46,000

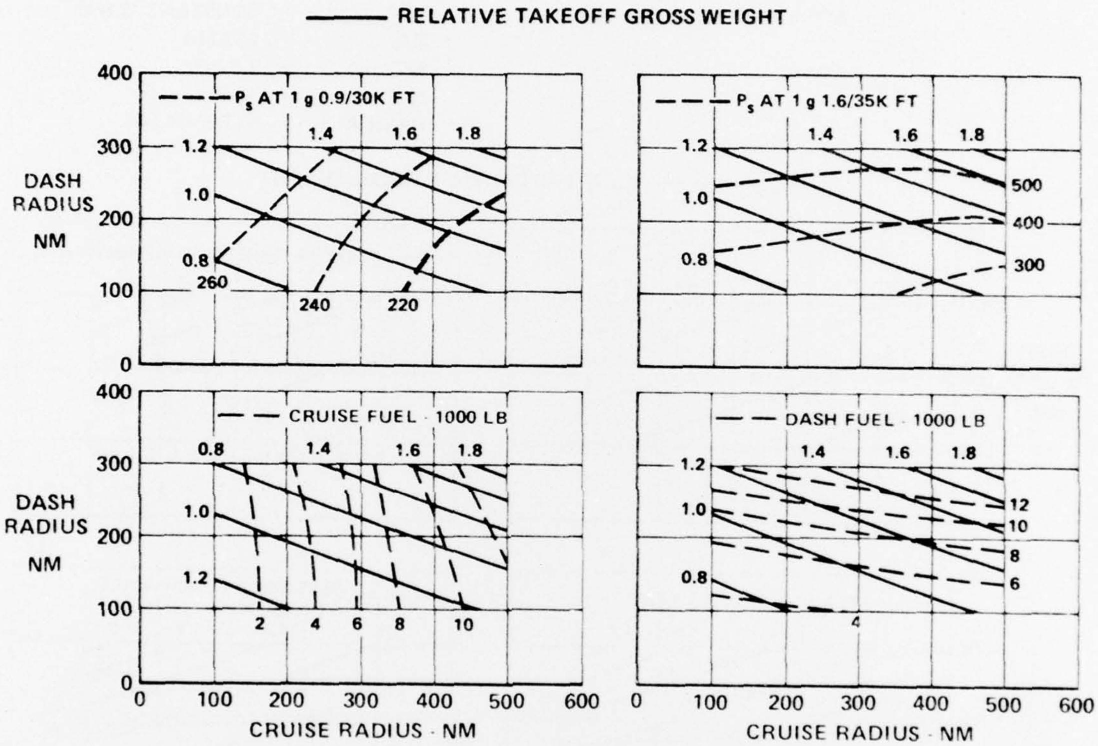

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FIGURE 33
REQUIREMENT INTERACTION VISIBILITY MAPS
P&WA VGT TURBOJETS

REQUIREMENTS		
DASH MACH	=	1.6
N_{zs} (DASH M&H)	>	1.2 g
P_s (DASH M & H)	>	5 fps

OPTIMIZED VARIABLES		
OPR	-	CONSTANT (25)
ASP	-	CONSTANT (1.0)
TIT	-	CONSTANT (2,600)
W/S	-	103-110
AR	-	2.8-2.9
Λ	-	43-46.5
DASH ALT	-	43,000-46,000

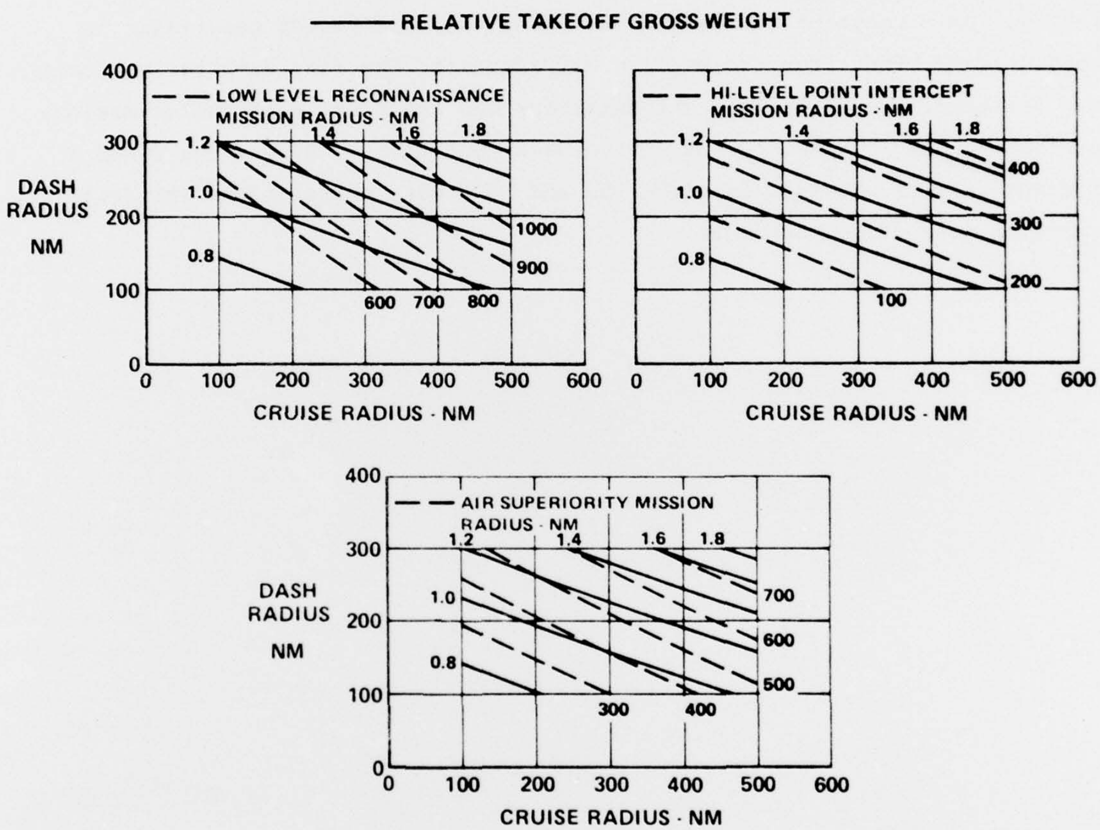

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FIGURE 34
REQUIREMENT INTERACTION VISIBILITY MAPS
ALTERNATE MISSION CAPABILITY
P&WA VGT TURBOJETS

The requirements used to constrain the optimizations, e.g., dash Mach number, maneuverability, alternate mission radii, etc., can cause large variations in the design and sizing variables selected. For example, Figure 35 illustrates the results obtained for M_{dash} = 2.2. In constrast to the M_{dash} = 1.6 results, the 1.2 "g" load factor requirement strongly affected the M_{dash} = 2.2 results. At large dash radii, the optimum aircraft T/W was determined by fuel sizing requirements and was sufficiently large to achieve the required load factor. For fuel sizing, the optimum T/W decreases with reduced dash radius, for a constant cruise radius, until the load factor constraint is encountered. Thus, for the M_{dash} = 2.2 aircraft, the long dash radius designs are selected by fuel sizing considerations and the short dash radius designs are compromised by load factor at the dash conditions. References 2 and 3 present results obtained from the DDA and P&WA data correlations for four explicit sets of constraints.

REQUIREMENTS		
DASH MACH	=	2.2
N_{ZS} (DASH M&H)	>	1.2 g
P_s (DASH (M & H)	>	5 fps

OPTIMIZED VARIABLES		
ASP	-	CONSTANT (1.0)
TIT	-	CONSTANT (3,200)
W/S	-	CONSTANT (112)
OPR	-	10-25
AR	-	2.9-3.05
Λ	-	43.5-46
DASH ALT	-	49,000-52,000

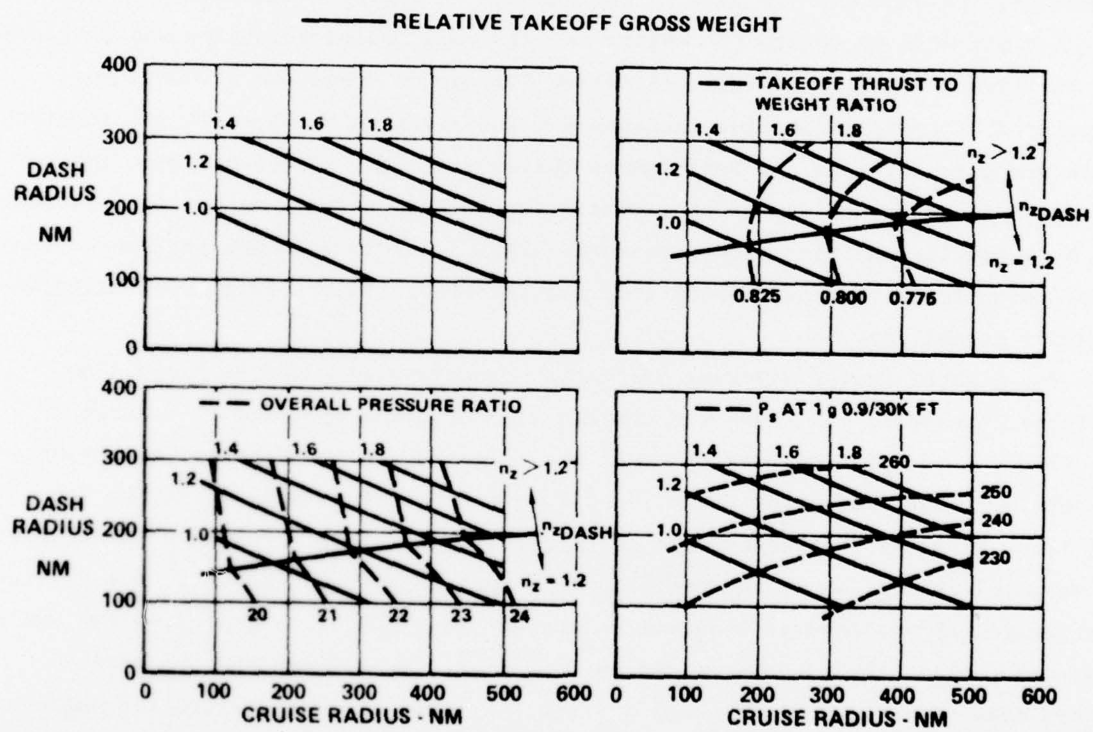

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FIGURE 35
REQUIREMENT INTERACTION VISIBILITY MAPS
P&WA VGT TURBOJETS

6. CONCLUSIONS

Systematic analytical procedures for fighter engine and airframe design selection have been developed and demonstrated. The resulting procedure can be effectively used in the definition of mission and performance requirements and for design selection in future fighter development programs.

Three aircraft roles were defined by MCAIR and AFAPL to provide a meaningful basis for design selections and evaluations of advanced engine concepts. The role definitions consist of mission profiles and radii, performance requirements, and operational limits in terms of maximum Mach number, dynamic pressure and load factor. The Tactical Strike, Air Superiority, and Intercept Roles were reviewed with the various USAF user commands to ensure that realistic future aircraft system requirements will be used in the subsequent engine evaluation.

A systematic procedure for engine and airframe design selection was developed and verified. The Fighter Engine/Airframe Evaluation Procedure accounts for propulsion system/airframe interactions and interactions between mission requirements and aircraft size and performance characteristics. Trade-off studies regarding the size and design characteristics of both the engine and the airframe can be accomplished using this procedure. Visibility is obtained for man-in-the-loop design definition and validation, and for tradeoffs of design complexity vs aircraft capability.

The Fighter Engine/Airframe Evaluation Procedure was used in Phase I to evaluate parametric families of turbojets and turbofans provided by General Electric. A turbofan powered aircraft was selected, on the basis of obtaining the minimum TOGW design for the mission requirements of a Tactical Strike Role. The size, geometry and performance characteristics of this aircraft were validated by means of design layout and performance computations. In Phase II, the Evaluation Procedure was used to evaluate design and requirement interactions for variable geometry turbine turbojets provided by Detroit Diesel Allison and the AFAPL. (These designs were obtained using a Pratt & Whitney Aircraft parametric engine design computer program.) An extensive data base of aircraft characteristics has been developed. These data, which account for design interactions, can be used for initial screening of aircraft with fixed or variable geometry engines.

The engine data provided for evaluation in this program were developed by three different engine manufacturers. The resulting differences in design duty cycle, weight analysis procedures, and design complexity preclude meaningful comparative engine concept selections. Because of the diversity of

the engine concepts, however, our evaluations indicate the following:

- o Variable geometry turbine turbojets produce subsonic cruise fuel consumption competitive to that of mixed flow turbofans as the result of reduced installation losses.
- o Variable geometry turbines, combined with airflow scheduling, permit supersonic dash with minimal augmentation and, thus, low fuel consumption.
- o The use of variable geometry turbines and airflow scheduling in turbojet engines reduces aircraft sensitivity to design variable changes and, thus, minimize risks associated with failure to fully achieve engine design objectives.

The engine/airframe evaluation procedure has been developed, validated, and is currently being used in MCAIR advanced aircraft design programs as well as in the contracted USN V/STOL Variable Cycle Selection R&D Program, contract N00140-75-C-0034.

APPENDIX

AIRCRAFT MATRIX DEFINITION USING LATIN SQUARE

The selection of an efficient engine and airframe design is based upon estimates of aircraft system size, cost, and performance. A large number of design variables can impact these aircraft characteristics, however, and analysis of all the aircraft configurations defined by all combinations of the important design variables would be prohibitive. Consequently, a statistical procedure called Latin Square is used to reduce the required configuration evaluations to a manageable number. This procedure has been used by both engine and airframe companies to select test conditions in past development programs. Latin Square is used to define the minimum number of aircraft designs, or test conditions, required to encompass the entire range of the important independent variables. The results of the analysis of these aircraft can be used to analytically define relationships between the engine and airframe variables and the system characteristics used in design selection. The following paragraphs present a brief example of the use of Latin square for definition of an aircraft configuration matrix.

To use Latin Square, the number of variables to be considered, n, must be a "prime number", i.e., an integer which is exactly divisible only by itself and unity.

For this example, we have considered five design variables and have selected five equally spaced values for each variable as shown in Figure A-1. For a five variable evaluation, there are $(5)^5$ possible designs and the Latin Square procedure is used to reduce the number of design evaluations required to twenty-five, $(5)^2$. These designs will encompass the entire range of values of all five design variables. Consequently, a twenty-five element matrix was defined, along with the variable matrix order shown in Figure A-2. The matrix order defines the location of the variable values within each element of the matrix, e.g., in this example, the number in the upper left corner of each element will always be a value of W/S and the number in the center of each element will always be a value of Λ.

The initial Latin Square matrix arrangement is defined by locating the minimum value of each design variable in the matrix element in the top row of the first column as shown in Figure A-2. Subsequently, the next larger value of each variable is placed in the top row of the second column. This procedure is continued until, finally, the maximum value of each design variable is located in the top row of the fifth, or the n^{th} column.

ORDER	VARIABLE					
1	W/S	30	40	50	60	70
2	AR	2	3	4	5	6
3	Λ	20	28	36	44	52
4	OPR	20	23	26	29	32
5	FPR	2.5	3.0	3.5	4.0	4.5

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FIGURE A-1
LATIN SQUARE - FIVE INDEPENDENT VARIABLE EXAMPLE

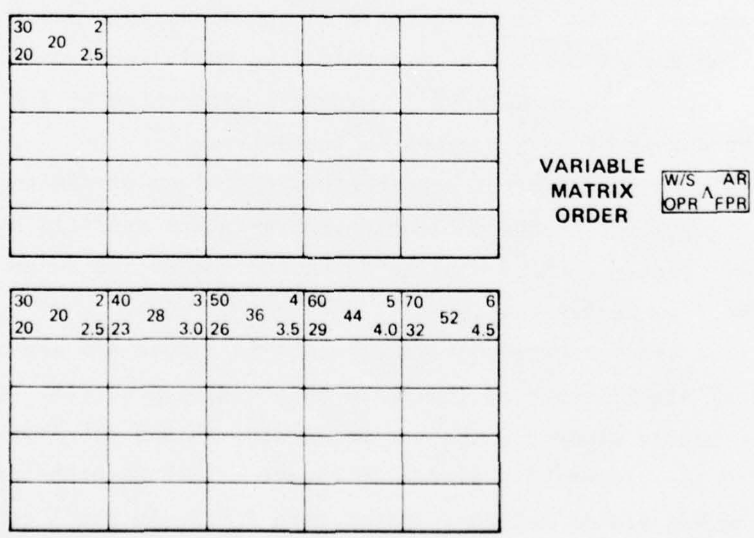

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FIGURE A-2
INITIAL LATIN SQUARE MATRIX ARRANGEMENT

The values of the design variables are located in the remaining matrix elements by means of the simple placement procedure illustrated in Figure A-3. The initial step in this procedure requires that the variable values located in the upper left corner of each element be moved down one row, successively, until each value is placed in each of the five, (n), rows. Thus, in this example, the W/S value of 30 is moved down such that it is located in the upper left corner of each element of the first column. As indicated, this process is repeated for each value of W/S until, finally, the W/S value of 70 is located in the upper left corner of each element of the fifth column. The second step of the matrix definition requires that the next variable in the order be moved right one column and down one row until each value appears once in each row and column. Thus, the AR value of 2 is moved from the upper right corner of the row 1, column 1 element to the upper right corner of the row 2, column 2 element. This process is repeated until finally, the AR value of 2 is located in the upper right corner of the row 5, column 5 element. This process is repeated for each value of AR until all values appear once in each row and column of the matrix. The values of the third variable in the order, which is Λ in this example, are moved right 2 columns and down 1 row until each value appears once in each row and column as shown in Figure A-3.

Location of the variable values is continued until each of the 25, or n^2, matrix elements contains a value for each design variable as shown in Figure A-4. The values of the final variable in the order is moved (n-1) columns to the right and down 1 row. Thus, in this five variable example, FPR values were moved right 4 columns, down 1 row until each value of FPR appears in the lower right corner of each element in the matrix.

A completed matrix of 25 combinations of values of design variables is shown in Figure A-4. Each combination represents a specific engine/aircraft design and, together, these designs encompass the entire range of values of each of the five design variables.

The five cross-hatched matrix elements in Figure A-4 are used to illustrate the physical significance of the Latin Square design matrix. Consider, for those five matrix elements, the variables W/S, AR and Λ. These variables are represented as intersecting planes in Figure A-5 where each intersection defines the W/S and AR values combined with $\Lambda = 28$ in the 5 crosshatched matrix elements in Figure A-4. These designs each contain a different value of W/S and AR and encompass the entire range of values of both variables. It is significant, however, that any one value of each variable is combined with

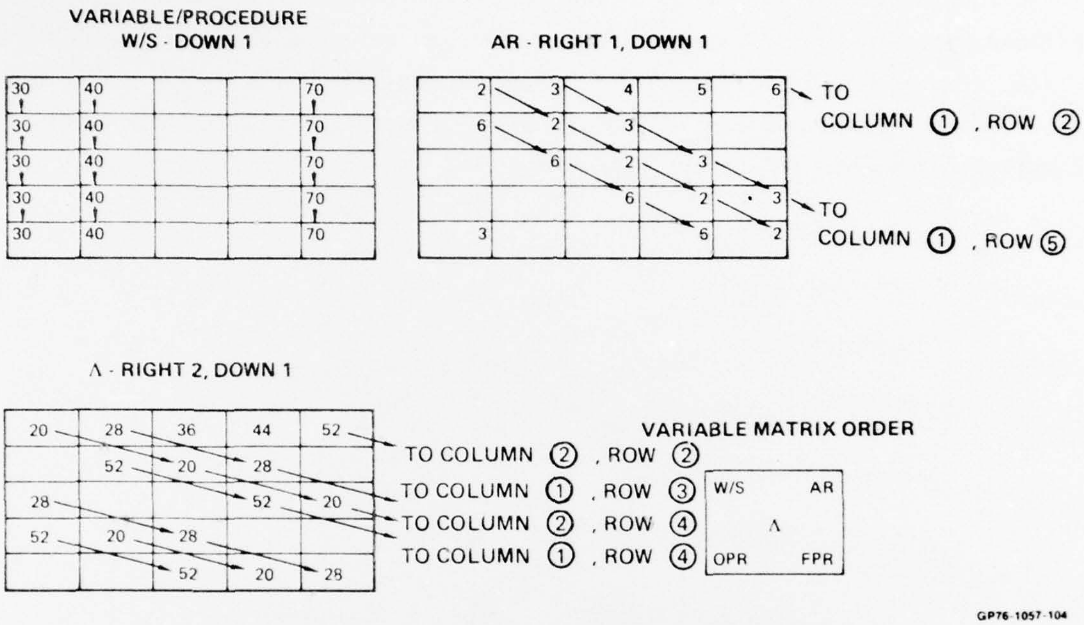

FIGURE A-3
DEVELOPMENT OF LATIN SQUARE DESIGN MATRIX

VARIABLE MATRIX ORDER

W/S	AR
Λ	
OPR	FPR

VARIABLE ARRANGEMENT

VARIABLE/PROCEDURE	
W/S	DOWN 1
AR	RIGHT 1, DOWN 1
Λ	RIGHT 2, DOWN 1
OPR	RIGHT 3, DOWN 1
FPR	RIGHT 4, DOWN 1

30 2 / 20 / 20 2.5	40 3 / 28 / 23 3.0	50 4 / 36 / 36 3.5	60 5 / 44 / 29 4.0	70 6 / 52 / 32 4.5
30 6 / 44 / 26 3.0	40 2 / 52 / 29 3.5	50 3 / 20 / 32 4.0	60 4 / 28 / 20 4.5	70 5 / 36 / 23 2.5
30 5 / 28 / 32 3.5	40 6 / 36 / 20 4.0	50 2 / 44 / 23 45	60 3 / 52 / 26 2.5	70 4 / 20 / 29 3.0
30 4 / 52 / 23 4.0	40 5 / 20 / 26 4.5	50 6 / 28 / 29 2.5	60 2 / 36 / 32 3.0	70 3 / 44 / 20 3.5
30 3 / 36 / 29 4.5	40 4 / 44 / 32 2.5	50 5 / 52 / 20 3.0	60 6 / 20 / 23 3.5	70 2 / 28 / 26 4.0

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FIGURE A-4
COMPLETED LATIN SQUARE DESIGN MATRIX

only one value of the other. An interpolation/correlation procedure must be used to provide information on aircraft configurations not included in the Latin Square matrix. For example, 25 engine/airframe configurations are defined by Latin Square while there are $(5)^5$ possible combinations of the design variable values. The SURFIT procedure described in Section 3.2 is used to obtain the design variable/aircraft system characteristics relationships required for meaningful design selection.

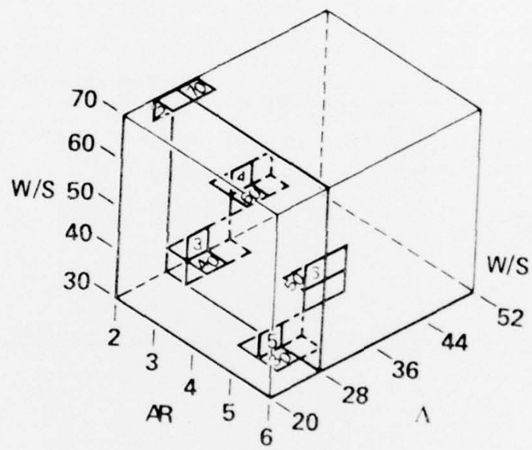

FIGURE A-5
LATIN SQUARE
AIRCRAFT DESIGN ARRAY

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